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1961 JOINT CONFERENCE WITH THE AIRPORT OPERATORS COUNCIL

PROCEEDINGS OF THE

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Journal of the

AIR TRANSPORT DIVISION

Proceedings of the American Society of Civil Engineers

PAPERS AND DISCUSSIONS FROM THE ASCE-AOC JOINT CONFERENCE "INCREASING AIRPORT CAPACITY", MAY 11-12, 1961, MIAMI BEACH, FLORIDA

Conference Organization

Technical Sessions Chairmen	- Robert Horonjeff - B. E. Nutter
Technical Sessions Programs	- W. M. Beadie - Ross A. Knight
Local Arrangements	- C. H. Peterson
Publications Committee	- W. E. Gillfillan

Vol. 87 No. AT 2

INCREASING AIRPORT CAPACITY
AN ASCE-AOC JOINT CONFERENCE

CONTENTS

(over)

The three preceding issues of this Journal are dated October 1959, May 1960, and March 1961.

Journal of the
AIR TRANSPORT DIVISION
Proceedings of the American Society of Civil Engineers

CONFERENCE REMARKS

Report of the AOC-ASCE Joint
Conference Committee

SYNOPSIS

The several introductory and background presentations made to the May, 1961 AOC-ASCE Joint Conference on Increasing Airport Capacity are presented. In the "Introduction," the general outline and the persons who planned the Conference are presented. In the "Welcome," the reasons behind the joint meeting of airport engineers and airport operators are set forth. In "Airport Capacity and Safety," the need for a broad, integrated, and cooperative approach is analyzed.

Note.—Discussion open until January 1, 1962. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Air Transport Division, Proceedings of the American Society of Civil Engineers, Vol. 87, No. AT 2, August, 1961.

INTRODUCTION

By Robert Horonjeff,[1] F. ASCE

As General Chairman of the Technical portion of this Joint Conference, the writer hopes that the technical program will be both interesting and stimulating. This is the first time ASCE has joined with the Airport Operators Council in conducting a conference on airports. Both the Executive Committee of the Air Transport Division and the Board of Directors of the Airport Operators Council thought that it would be of mutual benefit to have the operators of the nation's largest airports interchange information with the engineers who plan, design, and build them. For it is only through this exchange of information that engineers can better understand the problems of the operators and they, in turn, can better appreciate some of the engineer's problems.

The theme of this technical conference is "Airport Capacity." With the tremendous increase in air traffic that is forecast in the next decade analytical procedures must be developed for assessing the capacities of airports with their many configurations and air traffic control complexes. The engineers' charge is to arrange runways, taxiways, and other facilities so that we can increase the capacities of existing airports to the maximum possible extent. For we are quickly running out of space for new airports—both ground space and air space; furthermore, the costs are becoming enormous and the political complications are multiplying. Thus, before we recommend that a new airport is needed, we must be certain that everything possible has been done to increase the capacities of the existing airports.

Fortunately, the Federal Aviation Agency, recognizing the problem, has lent support to the development of analytical methods for better assessing airport capacity. This is, undoubtedly, a major reason for the growing interest in the subject of airport capacities that has been developing in the past two years among research men, both in educational institutions and in industry. The nature of this work to date and an appraisal of the work that needs to be done form the program of this Conference.

On behalf of the American Society of Civil Engineers the writer would like to acknowledge the marvelous cooperation received from the Airport Operators Council staff, particularly Tom Burnard, the Executive Vice President, and Russ Knight, Director, Technical Services.

Within ASCE, Mac Beadie, F. ASCE, has acted as Chairman of the Program Committee, (this Committee was responsible for the preparation of the technical program); Walter Gillfillan, M. ASCE, is Chairman of the Air Transport Division's Publications Committee (this Committee has the responsibility of assisting in the prepartation of the proceedings of this conference); George L. Smith, M. ASCE, is chairman of the local arrangements committee (this group worked closely with the AOC staff in making arrangements for this meeting; Ronald White, F. ASCE, is a member of AOC and is also the Chairman of the Executive Committee of the Air Transport Division; Thomas Fratar, F. ASCE,

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[1] Prof. of Transp. Engrg. and Research Engr., Inst. of Transp. and Traffic Engrg., Univ. of California, Berkeley, Calif.

is contact member to the Air Transport Division from the Board of Direction; and Don P. Reynolds, F. ASCE, is Assistant Secretary of ASCE.

WELCOME

By George De Ment,[2] President, Airport Operators Council

It is a sincere pleasure, on behalf of the officers of the Airport Operators Council, to open this joint conference of the ASCE Air Transport Division and the Airport Operators Council.

This is a remarkable opportunity for all airport operators and civil engineers in the field of air transport to share experiences and knowledge and, as a result, to do a better job for all our communities.

2 Comm., Dept. of Pub. Works, Chicago, Ill.

AIRPORT CAPACITY AND SAFETY

By Jerome Lederer[3]

INTRODUCTION

The opposite of capacity is congestion. The orderly, safe and expeditious flow of uncongested air traffic will be dependent, to an ever-increasing extent, on the ability of airports to receive it.

How safe is air transportation? There are many different ways to measure safety. Statistics in any form indicate that scheduled airline flying is well within the normal risks of living. The easiest proof of this is to assess the risk of the man most exposed to the hazards of flying—the airline pilot. Flying at the rate of 1,000 hr per yr he has a life expectancy as a pilot of over 1,000 yr. His life insurance premium is no more than that of a chess player.

As of May 1, 1961, the Boeing-Convair-Douglas jets have carried over 22,000,000 passengers approximately 35,000,000,000 passenger-miles with a loss of 136 passengers. This results in a rate of 0.4 passenger fatalities per 100,000,000 passenger miles. In one week the jet transports made by just one company will fly 230,000,000 passenger-miles.

CAPACITY AND SAFETY

From the standpoint of airport safety and airport capacity, however, an accident can close a runway. Furthermore, it is not the few fatal accidents that are important. It is the more frequent incident or non-fatal accident or potential accident that can close a runway or an airport to reduce or nullify its capacity.

Air congestion, well handled as it is, is so great that in selecting a site for a new airport the civil engineer must take soundings upwards as well as down. Before he digs holes for his foundations he must look for a hole in the sky. And we are only at the threshold of the problem of airport acceptance.

DEVELOPMENTS IN THE NEXT DECADE

In the next ten years or so aviation should expand in five different directions. four, and possibly all five, will effect airport capacity. It is doubted whether the ground facilities will ever catch up with the dynamic developments of the vehicle.

These five developments will be:

1. An increase of 20% in the size of the subsonic fleet, notably in general aviation (which is expected to increase from 75,000 aircraft to about 100,000

[3] Managing Dir., Flight Safety Foundation, Inc., New York, N. Y.

aircraft). The number of flights per yr is expected to increase from 18,000,000 to about 30,000,000. All-weather landings should be common at large airports within a few yr. The number of accidents or incidents should be expected to increase even if the "rate" of safety improves.

2. The advent of supersonic aircraft have quite an impact on airport facilities and management. Not the least of the airport problems will be those concerning public health with the rapid transit of disease, insects, and parasites. The high span loading of these aircraft may create vortices that will interfere with prompt take-off or landing of other aircraft, especially when temperature inversions exist.

3. The penetration of the short haul passenger market by steep gradient aircraft. This will call for special systems of navigation and traffic control that will have to be coordinated with control of airplanes on the ground as well as in flight. Coordination of traffic on the ground may well be the more difficult of the two.

4. The introduction of ground effects machines for off-shore or out-of-bounds rescue operations, for airport inspection, for delivery of goods and people to airports, and for many uses as yet undetermined.

5. The development of space vehicles with guided rockets that may carry mail will create problems, many of which are still to be uncovered.

These five developments should mature in the next ten yr. The first four will affect airport capacity by the mixed type of traffic, by noise, dust, turn-around time, and more accidents and incidents just when passenger railroads are being phased out of our lives and air busses enter. Space vehicles may have a favorable effect on air traffic control by improved weather reporting and better communication.

INCIDENTS VERSUS CAPACITY

Let us now consider a typical non-fatal incident that occurred on an airport recently. The weather was bad, the runway was wet with a thin coating of slippery dust, and the airplane couldn't brake in time. It swerved off the runway, and skidded to a turning stop with the nose wheel bogged down in mud just off the runway shoulders. What did it do to the capacity of that runway? It was closed for two days and many flights were diverted to airports hundreds of miles away.

In another case the weather was good, the pilot overshot, cracked up on the runway, and the runway was out of use for 21 hrs at one of the world's busiest air terminals. There were at least 23 such incidents in scheduled operation in 1960. The capacity of runways can be reduced by aircraft striking blast fences or dikes, by striking sharp curbs at the runway end, by wet and slippery conditions, by soft shoulders, and other design features that result in accidents or incidents. One might say that these should not be permitted. But these exist, they are permitted, and there are no easy remedies to some of these conditions. They result in incidents that close runways and reduce airport capacity.

The airport itself need not be at fault. Brake failure, undercarriage collapse, and steering gear failure caused runways to be closed several times in 1960.

Operational accidents and incidents on the runway, however, are not the only cause for reducing airport capacity. Runway capacity will continue to be af-

fected by snow, birds, slush, turbulence and vortices, failure of approach aids, airport power failure (even when duplicated, because the duplication is not carried down to the wires that feed the lights), poor taxiing techniques, mishaps at gate positions, in-flight emergencies such as stuck undercarriage or one engine out, a passenger ill, or a private pilot who has lost his way.

PRIVATE AIRCRAFT AND CAPACITY

In the political-economic environment in which we operate, the private pilot has and will probably retain access to airports used by the airlines. His equipment may not be built, installed, or maintained to the same standards as that used in airlines or large corporation aircraft, and his proficiency may be less than that of the professional pilot. Air carriers are required by FAA Act to perform their services with the highest possible degree of safety in the public interest, whereas for other aircraft operators the FAA Act calls for reasonable rules and regulations and minimum standards in the interest of safety. This is done to encourage the development of general aviation by avoiding overregulation. The philosophy behind this is that if a person wishes to accept risks to himself or his family, he is entitled to do so. This is what opened our frontiers and developed our industries, including aviation. When one's actions may jeopardize the welfare or safety of others who are innocent bystanders, the highest possible degree of safety is required.

It has been proposed that private pilots using busy air terminals meet minimum equipment requirements and that the equipment meet higher standards of reliability than now exists so that they will be less likely to create emergencies or endanger other air traffic by failure. If proof or statistics are available to show the need for better reliability and acceptance rates are affected by unreliable equipment, then the standards should be raised or such aircraft should be limited to airports designed for the private pilot where there is mutual understanding and acceptance of the risks involved. To a degree this philosophy is already in effect where airports require two-way communication for all private aircraft. Differences in standards should not be permitted to jeopardize the innocent.

Assuming that the equipment installed in private aircraft is reliable, the competence to handle it is equally important. Adequate standards of airmanship should be required. The various private pilots associations, the AOPA, NPA, Flying Physicians, and so forth, are encouraging higher standards.

It would be more desirable to reduce the complexity of ATC so that it would be as easy to approach Idlewild as Squeedunk. This may come, but it isn't here now.

GREAT NEED FOR SATELLITE AIRPORTS

Even with the best of equipment and airmanship, however, airport capacity could still be adversely affected at peak hours by the great differences in approach and landing speeds between samll aircraft and air transports. An excellent way to attack this problem is to attract private pilots away from busy terminals by providing more airports for their own use—satellite airports.

If this is so, then the entire aviation industry should support the new Federal Airport Act Bill S-1703. This allocates $7,000,000 per yr for 5 yr to pro-

vide landing facilities for general aviation. These are designed to attract the private pilot away from the congested terminals.

The FAA regulations prohibit Federal financial aid to airports where the adequacy of approach zones is not reasonably assured for the future. With increasing population pressure and rise in land values, planning for these airports should begin right now. The Airport Operators Council and the Air Transport Association should join with general aviation in promoting this mutually advantageous venture in the self-interest of all. N. E. Halaby, Administrator, FAA, had this to say before the Subcommittee on Transportation and Aeronautics, House Committee On Interstate and Foreign Commerce, May 9, 1961:

> "Recently this Agency completed a study, entitled 'Economic Planning for General Aviation Airports.' Among other things, it concludes that:
>
> 1. Large and medium hub communities need separate general aviation airports because of their very great air carrier activity, and
> 2. Important segments of general aviation tend to desert an air carrier airport when annual operations of air carriers there have reached 30,000 to 50,000."

An increasing number of air taxies and private aircraft are being used to make connections with airlines at the terminals. Even with reliable equipment and competent pilots, it seems unrealistic to use a $10,000,000 runway for a small airplane during peak traffic periods. To avoid interfering with the capacity of runway designed for heavy air transports, it has been suggested that a separate strip, not necessarily paved, say 4,000 ft long and with its own facilities, be provided for the private pilot. There is airspace around terminal airports that is never used by air transports. Special traffic rules, possibly VFR corridors, could be developed. There is strong evidence that this is feasible at LaGuardia-Flushing, at Washington National/Bolling-Anacostia, at Cleveland, and elsewhere.

Minneapolis-St. Paul meets both suggestions. It provides both satellite airports and a special strip for small airplanes at its main terminal.

All aircraft would have to be funnelled through the same air traffic control system under IFR condtions, so the special strip at the congested airport would be workable only in VFR. However, under IFR, private pilots prefer to stay away and traffic is reduced. The problem of marginal weather—not quite IFR, not quite VFR—exists as a collision potential. These rules should be reexamined. An arbitrary increase in ceiling and visibility may or may not be the answer. Other solutions might be sought, such as requiring a 500-ft ceiling over the outer marker.

The problem of cross-wind landing if only one strip is built should not be too serious, because private pilots are becoming accustomed to cross-wind landings at many private fields that have only one runway.

The airstrip at busy airline terminals is provided on the premise that private pilots have a right to land at air terminals, that air congestion creates hazard, and that it can be relieved by providing special facilities for private pilots in VFR weather.

REGIONAL CONCEPT—EXCESS CAPACITY

Returning to the closing of runways by accidents, incidents, and in-flight emergencies there will be enough of these to suggest that the acceptance rate

should not be dependent on the capacity of any one airport to solve the ATC capacity problem in a congested area. Even two or three airports that serve a metropolitan community may not be enough if all are subject to the same capacity reducing factor as an in-flight emergency or the loss of communications or a lost aircraft, when safety requires holding or diversionary procedures.

Therefore, it is questionable whether a metropolitan area such as New York or Philadelphia or Boston can provide satisfactory capacity each for its own needs during peak conditions at all times! Runways will be closed for the reasons mentioned. If these were rare occurrences, say, one in a million landings, then runway closing might be tolerable, but this is expecting too much. The patience of the air traveling public will be put to test by long delays. This leads to the conclusion that capacity should be considered on a regional basis. Not an air terminal for each city, but an air terminal system serving the megalopolis of the future to provide the necessary acceptance flexibility. A fine example of this exists in the electric power system. If a station fails in one part of the grid, another station is cut in to take over the load. Power stations are designed with excess capacity to provide for such emergencies. Can it be said that this is an unnecessary economic burden when measured against the loss of power to industry, to public safety, if excess power were not available in emergencies? Of course, the air safety interest in this is to relieve the congestion and collison potential that may occur in the heavy air traffic of the future if aircraft can not be quickly diverted to other airports because of lack of capacity. What would happen to traffic destined for Idlewild if it were closed at the peak period? Would Philadelphia, Boston, or Baltimore be able to handle it at their common peak period?

If excess capacity to meet emergencies is a valid concept, it means that the capacity of each airport in the regional system of airports should be expanded by some figure to provide reserve capacity. For example, it may mean constructing two runways where one may be ordinarily adequate. And, incidentally, that runway might be used for itinerant traffic. This sounds expensive but on a total cost basis, considering aircraft held up at distant points, the expense of holding, loss of valuable time of passengers, it might prove to be less expensive to have an over-capacity to meet emergencies than to satisfy normal peak needs. It certainly would be in the public interest, just as it is for the electric power industry to have reserve capacity. Incidentally, every transport aircraft has reserve power, also at considerable cost in the public interest.

BEDROOM TO BEDROOM

Excess capacity on a regional airport plan requires the solution to one other very important problem. The passenger should have a way to get to his ultimate destination with minimum delay no matter where he lands in the regional system. His convenience must be considered in terms not only of an air transport system but of an integrated transport system of which air may be only a part. How will he get home in the least time? I can visualize flocks of VTOL aircraft being deployed to handle the emergency traffic. Here we may see a battle between monorails and VTOL. Monorails have been used in Germany for about 60 yr. They are safe, fast, and reliable. The ground below can be used for other purposes. They create minimum noise and dust and require less skill and equipment than a VTOL. However, they lack the flexibility of a VTOL. It is difficult to conceive a monorail crossing the Hudson. A passen-

ger destined for Westchester County in New York landing at Philadelphia would probably arrive home quicker by VTOL than by monorail. If economics points toward VTOL/STOL, then we shall have further congestion and an air safety problem that has to be solved.

Air France proposes a monorail from Paris to Orly. BEA would like to see one at London. According to Lord Douglas of BEA, on the 220-mile journey between London and Paris, saving 10 min on the ground at each end is equivalent to increasing an airliner's cruising speed from 400 mph to 1,000 mph. BEA has offered to contribute $2,800,000 towards the cost of building a monorail to London Airport.

Rapid transportation from regional airports to the passenger's ultimate destination should be part of the planning. If a passenger living in Philadelphia, flying from Los Angeles, is diverted to Idlewild because Philadelphia is closed, he ought to be able to get to Philadelphia by rapid transportation, not rely on the railroad or bus. This means VTOL or equivalent.

HINTS AND DEVELOPMENTS TO IMPROVE ACCEPTANCE

Total efficiency of operation is obtained by eliminating many small inefficiencies. The following ideas are offered to stimulate thinking to retain planned capacity of runways.

Arresting Gear.—The adoption of devices such as arresting gears or the so-called "controlled mud puddle" would help reduce take-off and landing incidents. The arresting gear requires a tail hook that the industry may resist. The "mud puddle" consists of a pool of water at the runway ends. This is covered by a strong, flexible plastic sheeting. When the airplane overshoots onto this surface, the wheels create a bow wave that effectively decelerates the airplane.

Airport operators and airlines probably shudder at the extra costs of such devices. These may cost less than overrun areas. There is a great need to balance the costs to the operators against the financial advantages and efficiency of more dependable operations that such developments may produce, plus added safety. Runways might be closed less often, pilots would land or take off with a greater spirit of tranquility, there would be less chance of fire in an overshoot, better access to the airplane by crash crews than if it wound up in the boondocks.

Another idea advanced by the head of the research department of a very large aircraft manufacturer is to blow out the tires if the pilot feels he will run off the runway. Tires on jets have fusible plugs to blow out if the tires overheat. If these can be discharged at will and the tires deflated, the airplane should stop sooner. This has been shown to be true with large bombers that have landed with deflated tires.

Stones.—Stones are not dangerous but they can cause delays by damaging flaps and by engine ingestion. It has been suggested that tires for airport vehicles could be designed so that they would not pick up stones and deposit them on ramps and taxiways.

Monitoring.—Capacity and planned spacing between aircraft movements can be improved by uniform discipline in following good practices. This applies to taxiing and take-off as well as landing. Delays occur at take off while pilots run up engines or go through check lists. These are essential for safety. How-

ever, there are techniques to do this at times that will not cause delay. If not, then perhaps run-up pads ought to be considered. Time-motion studies of this and other operational delays should be made. Factual data is needed to sell pilots and operations executives on the need for instituting changes. A continuous system of monitoring should be instituted. It is possible to monitor landings and take-offs by photographing the Airport Surface Detection Radar, and reducing the data to a form that shows where delays are occurring. This will come in time at major terminals. GCA is a form of monitoring.

Quality Control.—It may seem far-fetched to suggest that improved quality control in the manufacture of aircraft accessories should affect airport capacity. All too often aircraft turn back because of the malfunction of some small instrument or gadget. The CAB has recommended that the FAA do something about this by requiring quality control in TSO's.

Taxiway Marking.—Pilots complain they get lost after they land. Taxi markings should be improved to reduce delay on the ground, especially at night and for pilots of smaller aircraft.

Target.—The wide use of visual glide slope indicators and the introduction of aiming points should reduce the numbers of accidents due to undershooting or overshooting. More ILS, the installation of proven aids to approach and landing are, of course, a must and there should be no problem about this at the airports of the future if they have duplicate sources of power. The problem is to accelerate their installation at airports currently used.

Language.—Language barriers that result in delays or uncertain approach may be reduced by radio teletype directly into the cockpit.

Snow.—New techniques of snow removal should reduce that factor. Snow is poured into cisterns of lukewarm water and comes out as water.

Birds.—A study of birds at airports may bring several solutions. The use of a sharp noise at proper intervals, the distribution of food that causes stomach trouble, the recording and playback of distress calls, and the use of foliage that does not attract birds are some of the ideas. The Nice Airport, according to the New York times, birds are attracted to the runways because they are more comfortable on the smooth concrete than on the pebbles that border the adjacent Mediterranean shoreline. The airport is building huge sandboxes over the pebbles, hoping that the birds will prefer sand to concrete.

Duplicate Power.—Power supplies are required to be in duplicate but the power lines, carrying current to runway lights and other traffic aids, are often single. Even at the busiest airports flare pots must be set out to replace runway lights while aircraft are held up waiting to land. The remedy is to see that duplication is carried right up to the lights or communication installation, if feasible.

Crash Removal.—Prompt removal of crashed aircraft to restore the airport to normal capacity is a considerable technical problem. One organization has developed a self-contained steel hydraulic lift platform that can be slipped under the fuselage, raised, and carted away by trucks.

CONCLUSIONS

1. From the standpoint of safety and efficiency it is important to provide uninterrupted flow of scheduled traffic to airports. Airport capacity should be adequate to avoid en route delays.

2. Ability to handle air traffic and airport traffic will be complicated by an increase in diverse types of aircraft.

3. Runway capacity, in spite of best planning, can be reduced and nullified by accidents, incidents, in-flight emergencies, weather, birds, power failure, and so forth.

4. The numbers of incidents or accidents are likely to increase (even if the safety rate improves).

5. A major effort should be made by all segments of aviation to support the construction of more airports to be used by general aviation aircraft, thus attracting them away from major terminals.

6. General aviation will continue to use major terminals; therefore, they should be encouraged not to affect capacity of the main runways, especially in peak periods, by providing special landing strips for them.

7. Investigate the reliability of communication equipment used in general aviation before determining if standards need to be raised. Review standards of airmanship required for safe operation in congested areas.

8. To reduce VFR collision potential in congested areas in marginal weather, re-evaluate the minimums.

9. The cost of devices and systems required to avoid the closing of runways should be balanced against the cost of closing runways. The total costs should be considered, not costs of concern only to special segments of the air transport system.

10. The capacity for landing and take-off should be considered on a regional basis rather than at the community or municipal level. Excess capacity is desirable in the public interest to provide flexibility for aircraft acceptance when an airport or airports are closed.

11. In a regional plan, consideration should be given to the total transport system rather than in terms only of aircraft operation. VTOL, monorails, should be evaluated to carry the passenger between his point of landing, if it is not his destined airport, and his ultimate destination.

12. Support is needed for Bill S-1703 which provides $7,000,000 per yr for 5 yr for airports for general aviation. After the bill is passed, the industry must strive for immediate planning and purchase of land before it is too late. This is vital to relieve the load on major terminals and thereby to improve safety.

A broad, integrated, cooperative approach is needed to the total problem of airport acceptance.

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DETERMINING AIRPORT NEEDS FOR THE FUTURE

By George DeMent[1]

SYNOPSIS

The steps in arriving at an airport master plan for an area are outlined. These steps include a traffic forecast, an existing-airport capacity determination, a study of methods of improving the capacity of the present airport, and planning for a new airport.

INTRODUCTION

The tremendous scope of the problem of determining a municipality's airport needs for the future is indicated by the recently released Federal Aviation Agency's 1961 National Airport Plan. This plan describes an estimated $1,082,400,000's worth of airport development in the next 5 yr, in order to provide a national system of airports adequate to meet the present and future needs of civil aeronautics. Included in this 1961 National Airport Plan is the FAA's estimate, through 1966, of 20 new air commerce airports, 399 new general aviation airports, and 75 new heliports.

A requirement of such magnitude generates another obvious requirement for individual airport master plans based on logical and expected growth. Such master plans have been in existence at most airports for years but they were, in many cases, little more than dreams because of the uncertainty of Federal financial participation in the plans, brought about by the policy of year-to-year Congressional appropriations. The new airport legislation provides, for the

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[1] Comm. of Pub. Works, Chicago, Ill.

first time, a five-year program of Federal aid. With this assurance of at least five years of Federal support, airport master plans can be made on a business-like basis.

MASTER PLAN

It is of interest to determine the sequence by which a municipality can develop a valid, business-like airport master plan. Basically, the sequence involves (1) a comparison of capacity of the present airport or airport system with forecast traffic, (2) if necessary, the increase of capacity of the present airport(s), by all known technological means, and (3) if the present airport(s), even at their ultimate capacity, cannot handle forecast traffic, preparing for the eventuality of an additional airport or airports.

This basic planning sequence is fundamentally the same process required in road or highway development. The similarity between airports and highways ends here, however, and when one moves into the airport planning field one finds, not only a change in terminology, but two completely new planning factors. In highways one is concerned almost exclusively with density of traffic, with little regard for either the traveler's personal comfort or the fueling or maintenance of his vehicle. In airports, on the other hand, it is found that, in addition to providing operating surfaces for the increased density of traffic, that traffic's payload must be handled, be it people or cargo, plus facilities for servicing cargo and people and, in many cases, maintaining the air vehicle itself. These "added attractions" are what make the airport business so challenging.

Traffic Forecast.—The most fundamental planning factor in airport development is the traffic forecast. This forecast must include the following:

1. Total number of aircraft, including peak-hour traffic.
2. The aircraft "mix" -- the percentages of the total number of aircraft comprised by air commerce, both passenger and cargo, and general aviation. Also to be considered in this "mix" are such trends as the current one toward fewer passengers - carrying aircraft but more passengers per aircraft.
3. Is the traffic forecast itself reasonable in view of inherent limitations in the air traffic control system? It is one thing to forecast a certain density of traffic based on the traffic-generating capability of the metropolitan area, but if the airport complex and air traffic control system limitations are such as to indicate a lower maximum density of traffic, then the latter would be the limiting factor.

Airport Capacity.—The next planning step is to ascertain whether or not the present airport or airport system can handle both the amount and "mix" of the forecast traffic. Are the approaches suitable for the types of aircraft? Will the runway, taxiway, and servicing area layouts handle the peak-hour load? Is the terminal building adequate for passengers and the air cargo terminal facilities adequate for the air cargo requirements? Are the servicing facilities sufficient, both in total area and specific design features?

Improved Airports.—If the foregoing planning considerations indicate that the present airport or airport system is inadequate to handle the traffic forecast, what can be done with this present airport or airport system to increase its capacity? Can runway extensions, new or parallel runways, high-speed exit taxiways, or enlarged bypass aprons be utilized to increase the airport capacity? Can improved landing aids, such as vertical glide slope indicators and

touchdown zone lighting smooth out the traffic flow by reducing the percentage of diversions? Can additional gate positions or rearrangement of the present terminal building, maintenance area, and air cargo complex be utilized to reduce turn-around time?

Additional Airports.—If, in spite of any and all new ideas, it is obvious that the present airport or airport system cannot handle the traffic, we finally arrive at the obvious answer -- a new airport.

PLANNING A NEW AIRPORT

The first two questions with regard to planning a new airport, when the need for such becomes apparent, will have been answered in the preceding planning sequence. These two questions are Timing and Mission. If the present airport or airport system will be adequate, for instance, only until 1965, then 1965 is the target date for commencement of operations for a new airport. Because new airports do not spring up over-night, a municipality might find that work must be started on the new airport immediately. In the case of the Port of New York Authority, for example, it was determined that the present airport system would have to be augmented by another airport no later than 1965 and that a five-year lead time was required to have the additional airport operational; this is a most optimistic lead-time estimate. Although the mission of the new airport may not be determined quite as readily, it should become apparent in the planning which is the bottleneck: passenger handling, cargo handling, or general aviation? The decision as to the mission of the new airport will be based largely on the forecast of specific shortcomings of the present airport or airport system. With the timing and the mission determined, then we come to the question of site selection and specific planning of the new airport by function.

Site Selection.—Included in the site selection considerations are the following items:

a. Amount and type of air traffic;

b. Designed acceptance rate of the airport;

c. Air traffic control criteria, including the location with respect to air space, airways, let-down and approach corridors, and so forth;

d. Runway lights;

e. Overall airport layout, including runway arrangement and orientation and relative locations of terminal buidling, air cargo facilities, hangars, fuel farm, and so forth, as well as overall future stage development;

f. Terrain features - overall size of the available area, the topography and the availability of obstruction-free approaches;

g. Access to city utilities, including sewage disposal;

h. Distance and time from new airport to city, including types of ground transportation and a comparison between the existing and required limited access highways; and

i. Aircraft noise effects on neighboring communities, including zoning possibilities, coordination between airport management and city planning and housing authorities, and airport control of construction and approach areas.

Specific Planning for Airport by Function.—The functional areas envisaged here are: landing area, passenger terminal area, cargo terminal and industrial area, and airport operations and maintenance facilities.

Landing Area Development.

1. Runways - number, orientation, configuration, lengths and widths, design strength, types of pavement, function (instrument, general aviation, and so forth), general lighting and marking considerations, high-speed exit taxiways and taxiways and stage development, including possible future use of either displaced thresholds, arresting devices or both.

2. Terminal navigation aids, both electronic and visual.

3. Taxiways, location and design (with respect to turning radii of aircraft), strength, width, and stage development, corresponding with the runway stage development.

4. Hold and bypass aprons; capacity in terms of aircraft — bypassing requirements at specific runways.

Passenger Terminal Area Development.

1. Overall concept of the terminal building in relation to aircraft servicing areas — will they be connected or will they be separated, with mobile lounges or underground tunnels to the satellite servicing areas being utilized? Are separate terminal buildings for domestic and international flights envisaged? How about separate terminal buildings for individual air carriers? What are the plans for facilitation of interchange passengers (international to domestic; fixed wing to helicopter, and so forth).

2. Terminal building — what is the capacity and stage development in terms of passenger and aircraft gates? What is the functional design for passenger flow, both domestic and international, and vehicular flow? What is the overall configuration, including the number, size, and location of aircraft servicing aprons? What allowances are made for the amount and location of government-free space? What stage development is foreseen?

3. Aircraft servicing considerations — is it planned to utilize permanent airline gate assignments, or assign them on a first come, first served basis? What restrictions, if any, will be placed on jet aircraft taxiing into and out of the gates? Will this generate a requirement for jet blast fences? Will this fueling be done by truck or hydrant? How accessible are the servicing areas to associated airline ground vehicles?

4. What will be the arrangements for vehicular parking areas, airport hotel or motel and other miscellaneous passenger services, such as chapels and animal confort stations?

Cargo Terminal and Industrial Area Development.—Will air cargo be handled at a separate facility or in a part of the terminal building? What is the overall air cargo terminal configuration, functional design, and layout? What stage development can be anticipated?

Airport Operation and Maintenance Facilities.—Where will security, airport maintenance, rescue and fire fighting personnel, vehicles, and equipment be located? What sort of on-airport vehicle access roads are visualized?

DISCUSSION[a]

FROM THE FLOOR.—DeMent has presented a long list of airport requirements and planning needs. In planning O'Hare Airport were there enough

[a] The full discussion from the floor was tape recorded, but for the sake of clarity and brevity the remarks were slightly condensed and, occasionally, paraphrased. In some cases the identity of the discusser could not be determined.

sources of information? For instance, were the consulting engineers retained by the city, the airline engineers, and the FAA in a position to give all the answers needed in planning O'Hare? If not, where was the information obtained?

GEORGE DE MENT.—There is not sufficient technical experience in consulting groups and engineers in various airport organizations to provide most of the answers. This was not the case, however, in 1946-1947 when O'Hare was being planned.

As evidence of the lack of information available at that time, the first master plan called for ten tangential type runways. Not too long ago it was found that this layout was impossible because the available airspace couldn't support ten runways, so the master plan was cut back accordingly.

Another unknown was eventual runway length requirements. As recently as 1958, 8500 ft was stipulated to be the longest runway required. In August, 1961 a 12,500 ft runway opened for flights from O'Hare to Europe by jet.

This serves to emphasize the changing and dynamic field of airport engineering and operation. To do a real job, we must glean all knowledge available; airport planners must call in the consultants, the manufacturers, and the airlines, in short, the entire community of airport interests. Thus the planning tools are available, if all are considered and properly used.

ROBERT HORONJEFF,[2] F. ASCE.—In the next decade there will be problems caused by additional airports and so-called "regional airports" located far from town due to noise and airspace considerations. It is understood that the forecasts for the next decade indicate that the majority of the traffic, at least domestically, is going to be short-haul. Present airports are about as close in as they can be, and short-hual passengers are the ones that don't want to go too far; they want to reduce their ground time to a minimum. Therefore, these out-of-town, regional airports, built to serve long-haul traffic, actually produce less than the short-haul traffic, the latter being by far the most predominant. We have a dilemma of keeping ground-time down for these people; this is why it is necessary that we do everything we can to increase the capacity of our existing airports, because the short-haul traveler is the predominant domestic traveler.

GEORGE DE MENT.—This is entirely correct. One answer to the out-of-town airport is, of course, to plan for expressways from the airport to downtown, concurrently with the airport master plan itself. For instance it took about five years, in Chicago, to build the Northwest Expressway. As a result of this long-range planning, plus implementation by many means, one can now get from O'Hare to the heart of the Loop in 25 min.

With reference to close-in airports for short hauls, it is felt that Midway will maintain its importance in Chicago, and that airplanes will be developed that can continue to utilize Midway for short and medium haul traffic.

FROM THE FLOOR.—A question was raised as to what airports either have animal comfort stations or are planning to provide them, the following information was given:

New York International Airport has an animal receiving area, financed and built by the ASPCA on land leased from the Port of New York Authority.

2 Prof. of Transp., Inst. of Transp. and Traffic, Univ. of California, Richmond, Calif.

At Los Angeles, airport authorities have talked with local ASPCA representatives who are hopeful of providing a $300,000 facility at Los Angeles International Airport.

Honolulu International Airport authorities are planning a similar though smaller facility.

Journal of the
AIR TRANSPORT DIVISION
Proceedings of the American Society of Civil Engineers

IMPORTANCE OF REGIONAL AIRPORT SYSTEM PLANNING

By Ray O. Kusche,[1] F. ASCE

SYNOPSIS

Most urban areas demand an adequate air transportation system. This system will result in problems that call for joint action. The development of a plan is the responsibility of all communities that are served by the airport.

INTRODUCTION

The planning for airports in the past may be likened to this story—

"A man passing through a small town saw indications of amazing marksmanship all about - on trees, barns, and fences - each with the bullet hole in the exact center. He asked to meet the expert shot. It turned out to be the village idiot. 'This is sensational. How in the world did you do it?' asked the visitor. 'Easy as pie,' was the answer. 'I shoot first and draw the circles afterward.' "

For the purposes of this paper, a Regional Airport System may be described as an integrated arrangement of all types of airport facilities for a large geographical area, encompassing many political jurisdictions. It may be interstate as well as intra-state. The system must be concerned with helistops,

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general aviation airports, and the large intercontinental facilities. It must, further, be very cognizant of existing military airports and related facilities.

REGIONAL AIRPORT SYSTEM

The plan for a Regional Airport System is usually concerned with an area that is more urban in character than rural, and it is evident that transportation is the key to urban development. It has been said that the trend toward an urbanized United States will continue. Some estimates indicate that of the 30,000,000 population increase of the next decade, 4 out of 5, or 24,000,000 additional people will live and work in an urban environment.

Our high standard of living and levels of economy are related to this trend toward urbanization, which in the first half of the 1900's, has been primarily due to motor vehicle transportation.

But in 1961 the concern is in providing facilities for the air transportation system that is now accounting for more non-commuter passenger miles than either bus lines or railroads,—actually about half of the total, at present—and increasing daily.

The concern, too, is with the lack of appreciation of the importance of a plan for an air transportation system by many who are responsible for guiding the growth of urban areas. Theirs is a failure to understand that air transportation facilities are a public necessity, and that these large urban complexes require convenient air transportation for the conduct of business and normal communication and will indeed be important to the future growth of our urban areas.

Attention was directed recently to a Report by the Department of Commerce on the future development of the San Francisco Bay Area, 1960 - 2020. Without knowing the exact details of the assignment, it is noted that land use plans, population maps, circulation systems, drawn for this area at 10-yr intervals until the year 2020, do not indicate airport requirements or locations, even in schematic form. The only references to air transportation have to do with the feasibility of some filling of tidal lands along the Bay-front for possible future airport expansion. Not even the airport studies prepared for the Bay Region in the late 1940's were identified as being a factor in the plans prepared. Future airport sites have also been noticeably lacking from many other recent regional land use plans.

There is an obvious need for a comprehensive airport plan and paralleling action programs in many urban areas that should be coordinated with all other aspects of land use planning.

History records the fact that there were many cities that became prominent because of their natural or strategic advantages only to fade into oblivion because of their failure to take advantage of developments in transportation and communication. An illustration is the decline of certain Mediterranean cities of the 16th Century, following the discovery of new trade routes to the East.

Also, the Erie Canal gave the Port of New York its start on the road to supremacy in the world of transportation through helping develop the Port District as a great railroad terminal.

Today (1961), the airport is becoming the catalyst in the same manner that, historically, the railroad junction, the confluence of rivers, natural harbors, and other transportation centers became catalysts, creating the reason for

communities. As catalysts, airports require service and conveniences that now must be part of our urban planning. Office buildings, hotels, and other commercial and industrial activities are demanding locations near airports because air transportation is the key to their operations.

Improved land, which a few years ago near Los Angeles International Airport was $3,000 an acre, is now $75,000 and more an acre, reflecting the increased importance of air transportation in community activity.

Any of the implications of the revolutionary influence that airports will have on the future of modern urban areas cannot be neglected

There have been a number of reports and plans for Regional Airport Systems. These have been primarily for urban centers such as for areas including New York, Philadelphia-Camden, New England, San Francisco, Detroit and others. As the 'urban sprawl' creeps over the metropolitan areas many of us have been concerned all along with the location of airports as an integral part of these areas.

It is not particularly difficult to plan the airport itself, but the location in relation to the urban growth patterns is difficult to agree on, and the location with respect to other community services is critical. Particularly critical is the necessity of planning airports in areas that have not yet been suffocated by urban growth so that proper activities can be planned around the airport rather than forcing the airport into existing uses that may be incompatible.

The necessity for regional planning becomes apparent when observation is made of the efforts of individual cities or counties to create or discourage airports. New general-aviation airports are extremely difficult to finance through individual city or county channels. Highways receive funds due to pressures, but there is a general lack of understanding of the important role air transportation plays in the economic well-being of the community, even in those cities that see themselves as centers of business and industry.

A case in point in Orange County, Calif., concerns the effort of a local Chamber of Commerce of a major city to enlist all other Chambers in the County to restrict the runway length proposed in the Master Plan for their only feeder-type airport, merely because the main street at the outskirts of the community will have to be slightly re-aligned to provide required safe clearance from the end of the proposed runway and to insure no interference with the instrument landing system. This County has the most rapid urban expansion of any in the United States and has only two general-aviation airports. Presumably, the business men on the main street believe they will be hurt because the highway is 1,000 ft longer. But they will be hurt more if they don't have good airport facilities in this rapidly expanding urban area.

Then, there is the small city that sees in the airport a panacea to cure all their economic problems, a place to attract people and industry that will build up their town, but who, because of the relation to other airports, poor surface transportation or an inadequate economic base, have no business getting involved. Others see the airport as the source of complete community ruin because of the hazards, noise, traffic, and other problems. Few are concerned with whether their having or not having an airport makes sense in relation to the over-all demand for aviation facilities in their Regional Area.

The Pacific Southwest and particularly the Southern California area is an area that is continuing to experience a great population influx due to the reported general movement of people to warmer climes and the technological changes that are forcing people into urban areas. Here is a typical regional area that needs to think in terms of an airport system.

The seriousness of the transportation plight in Southern California is attracting the attention and increased concern of a number of influential groups. Recognizing that the problem in Southern California is the widening gap between available airport facilities and those needed to accommodate Southern California's growth, it is necessary to undertake a program of research and analysis that will serve as the basis for a long-range development of an airport system. Current efforts along this line in the airport planning field are being increased because of the subject of selecting a site for a second intercontinental airport to serve the Southern California area.

The Los Angeles Chamber of Commerce Aerospace Committee has been active in sponsoring a planning study for this purpose and has been joined by responsible public officials in the seven counties to pioneer a study and recommendation that will be in the interest of the whole Southern California area. Here is an example of regional cooperation for this single purpose. Included with the recommendation for a second International Airport will be a plan for the creation of an integrated airport system.

In Southern California an urban sprawl extending from Santa Barbara on the north to San Diego on the south is being referred to as a future 200-mile long "megalopolis." This area poses a fantastic problem in regional planning for all agencies concerned with land use. The whole urban complex is growing around only one transportation system—the automobile and a system of freeways.

Within this potential megalopolis we have a multitude of separate jurisdictions; the State of California over-all, a group of seven different counties, and a multitude of large and small cities. All the people within these jurisdictions demand transportation, but those to be inconvenienced by the installation of any system don't want it. The general attitude is—"Put it in the other fellow's backyard!"

The question that obviously comes up is the extent to which air transportation can serve in the mass transportation field in urban areas. Because as yet there is no foreseeable aircraft that can provide for this need, we must be content to think of freeways and major highways as the primary means of communication for many years to come. And we must further think of a system of airports in a region as an extension of this system, plus the fact that a monorail or other rapid transportation method may be integrated into the future pattern.

Some of the answers to the transportation problem lie in the land use planning and control field. In other words, planning for completely integrated communities in which people do not have to travel great distances to work, shop, or for recreation, and all utilities and services are concentrated. This, in turn, would provide capacity on the freeways for their proper function of connecting these urban centers and providing easy access to functions such as airports.

The efforts of the Federal Aviation Agency, through the National Airport Plan, to maintain a semblance of order in at least those airport facilities that are subject to Federal Aid should not be forgotten. Actually, the Federal Agencies are pleased to have the benefit of detailed studies for regions by others so that they may better allocate the funds available toward a sensible system. The requirements of airspace approval for new airports is also helping to minimize conflicts.

The planning of a Regional Airport System is subject to research and analysis techniques to forecast the expected activity, determine the types and number of facilities required, and methods of administration and financing usually

for a period of 20 yr to 30 yr. The expected activity would include forecasting number of passengers and amount of cargo, making origin and destination studies, and estimating commercial and general aviation requirements. The types and number of facilities required would be related to the capabilities of existing airports and the approximate locations of new facilities would be proposed.

Thus far, the creation of a Regional Airport System stays fairly free of the real fight, that is—the selection of the specific airport locations including the resolution of political, planning and engineering factors, and the methods of administration and financing.

Mixed in with these considerations are two related subjects that require the finest of crystal-ball gazing, that is, the determination of existing and proposed jurisdictions in the airspace including airways, control zones, approach zones, traffic problems, and the like. Incidentally, it has been estimated that in the Southern California control zone there are some 900 aircraft in the air during a peak hour.

The other subject is the types and characteristics of future aircraft that must be accommodated. In the recent Senate hearings regarding appropriations for the National Aeronautics and Space Administration, it is noted that the distribution of Research Center effort includes 5.4% for VTOL and other special aircraft, 11.4% for supersonic aircraft, 5.0% for hypersonic aircraft, and 3.2% for subsonic aircraft.

Roughly, 25% of research money, then, is for manned aircraft and certainly a large part of this will support research for a large economical transport in the 2000 mph range as well as for VTOL and other special aircraft that will probably have special utility for short-haul commercial transports.

This Government research is undoubtedly being paralleled by aircraft manufacturers and others so that we will have a new set of equipment around which to plan our airport systems in the next decade.

By delving far enough into this volume of proceedings, it will be found that there is serious discussion of the possibility of delivering mail by rockets. So here we are, just about to get all first-class mail on commercial aircraft, and consideration is being given to taking it off and putting it onto another vehicle. This activity should certainly pose some interesting launching and landing area requirements in the urban complex.

The supersonic transport is reported to be about on our doorstep and although it may fit on the existing intercontinental airports, what about whether it can be a good neighbor to present land uses around an airport; can 2000 mph traffic be mixed with present traffic, and really is it important to be able to move between two distant points such as Los Angeles and New York in $1\frac{1}{2}$ hr when it takes an hour, on the average, to get to the airport on our present highway and freeway systems?

In this connection, it is interesting to consider the magnitude of the access problem at Los Angeles, for if 7,000,000 passengers travel an average of 30 miles each trip, this is over 200,000,000 access miles a year. This certainly points out the necessity for the Regional Airport System to be coordinated with other transportation systems.

But maybe Southern California is fortunate in one respect. By delaying this long on the initiation of planning for a second intercontinental airport, possibly it will be determined that because of supersonic aircraft nuisances the location for a new airport should be in Death Valley where land is really inexpensive

and there are no neighbors—yet. Then all the existing major airports can be feeder airports,—but I suspect this wouldn't be received so well by Los Angeles International Airport.

At least if this happened, the airport would be there first and assuming we now know what to do, possibly the community that inevitably would be there could be kept out of the approach zone.

Looking toward the future, we must base our thinking on the best judgment we have, realizing that no one has sure answers. Probably drastic remedies will be required to meet the future needs of air transportation in the same manner that drastic remedies have been found to be required to accommodate automotive transportation in our urban areas. Planning now for a Regional Airport System, especially in urban areas, will help minimize the extent of the remedies required.

CONCLUSIONS

All realize that planning for individual airports is important, but to summarize this very general discussion, a few of the reasons why planning in terms of a Regional Airport System is important should be stated:

1. Most urban areas demand an adequate air transportation system because the basic geographic, economic, and population facts about the region show that aviation is important to its future development, and that the demands for all types of aviation services will continue to increase. If a region is to benefit from greater future aviation activity, it must make provision for adequate airport facilities. But competition for land is tremendous because the type of land required for airports is the same as for residential, commercial, and industrial uses. This, of course, means new airports in urban areas are costly to develop and also means that the special requirements of airports must be integrated with all other phases of land use planning.

2. The airport problems in a region call for joint action because they go beyond local political boundaries and require regional policies to plan and effect their solution. Particularly, is it apparent that the financial requirements for the development of new airport facilities, at least major airports, must be equitably distributed among airport users in the various political jurisdictions served by the system. Most individual political jurisdictions do not have the financial ability to create and support major airports. On the other hand, the jurisdiction that has the airport within its boundary will benefit greatly because business and industry tend to seek communities with the best in air transportation. However, it will also have the noise, nuisance, and hazard problems.

3. The development of a plan for a Regional Airport System will avoid the creation of separate airports by individual jurisdictions that could result in inconvenience to those requiring air transportation if not coordinated. For example, separate airports located near each other may reduce the frequency of airline schedules at each airport. In addition, the success of supporting facilities could be better assured by consolidation. Of considerable importance is the fact that air space problems could be simplified.

4. Without a plan for a Regional Airport System, including administrative authority, serious imbalances in the required airport facilities as a whole

could result because of multiple jurisdictions and responsibilities. For example, in Southern California there is a complexity of agencies concerned with airports. The Federal and State governments as well as county, municipal, and private interests overlap in various aviation functions such as those concerned with airport location and design, aircraft operations, and airport access. Multiple authority could result in surpluses or shortages of airports, airports not located in relation to the area served and air space conflicts.

5. The physical problems of locating airports make it necessary to consider their development on a system basis, for not all jurisdictions are equally well situated from the standpoint of topography, access, weather, and other factors.

The character of our urban areas in the future will be shaped in great part by the manner in which we face up to our transportation needs, which will permit this vast majority of our population to live and work in an ever-growing urban complex efficiently and with the amenities of American living—toward which we strive for ourselves and our children.

But in view of the ever-changing nature of air transportation equipment and facilities, a statement by Robert Moses, having to do with another subject, appears to be appropriate:

> "Don't let's try to be TOO farsighted. The Gloomy Gus weeping into his beer prophesies that the next generation, if indeed we survive total war, will be subject to compulsory birth control, eating plankton, drinking desalted sea water and euthanasia. Let's not be too lachrymose, lugubrious and fatalistic, and don't let's dwell too much on the horrors of the distant scene. As Cardinal Newman said: 'One step enough for me!'
>
> "There is a vast amount of nonsense talked by these sideline observers about our proverbial lack of vision, without which the Good Book says the people perish. The wiseacres have just discovered population explosion, suburban sprawl and blight, regionalism, metropolitan complexes, the Roadside City and the continuous megalopolis stretching from Portland, Maine to Miami, Florida, Seattle to Mexico City, Dan to Beersheba, Kashmire to the Deccan, and Land's End to John O'Groat's. Every sophomore talks glibly of such things and the architectural schools turn loose budding Frank Lloyd Wrights and Corbusiers who can at once save the countryside and fill it up with happy people.
>
> "All this is old stuff to the professionals who know from bitter experience that it takes nerve, guts, persistence and luck to realize any workable regional system."

DISCUSSION[a]

In response to a question as to whether or not the presence of a general aviation airport served to attract local industrial development, Mr. Kusche

[a] The full discussion from the floor was tape recorded, but for the sake of clarity and brevity the remarks were slightly condensed and, occasionally, paraphrased. In some cases the identity of the discusser could not be determined.

cited two examples on the west coast where this was the case. In one case the airport led to the creation of a very fine economic base for an entirely new community. In the other case the airport was located specifically in an industrial area and has been an important factor in attracting more industry.

Although reference was made to Federal funds being available for communities' comprehensive regional plans and for special plans such as economic base or mass transit development, no one knew of availability of such funds for regional airport planning. The seven-county study now being started in Southern California is financed by contributions from various Foundations and from the counties themselves.

Journal of the
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AIRPORT DESIGN BY ECONOMIC ANALYSIS

By Paul H. Stafford,[1] F. ASCE, and Martin A. Warskow[2]

SYNOPSIS

The factors that affect practical airport capacity are enumerated, and quantitative examples of their effects are given. An analysis technique is described for accurately predicting the practical airport capacity in terms of operating rate and delay. This technique is then used to show how economic analysis can be used to determine when a proposed project can be economically justified, or which of several possible solutions is the most economical.

INTRODUCTION

The Curtis System Engineering Team in their report, "Modernizing the National System of Aviation Facilities," stated "It is vital that we determine ultimate runway capacity to more accurately plan for long-range development of adequate airport facilities on a schedule which will meet the projected increase in traffic."

Early in 1959, the Bureau of Research and Development requested proposals to study the subject of airport capacity, not only to determine the ultimate capacity but also to develop a technique of relating operating rates to the resulting delay. The first phase of this work was completed and reported on in July, 1960 to the FAA Bureau of Research and Development.[3]

Note.—Discussion open until January 1, 1962. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Air Transport Division, Proceedings of the American Society of Civil Engineers, Vol. 87, No. AT 2, August, 1961.

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2 Consultant, Airborne Instruments Lab., Melville, Long Island, N. Y.

3 "Airport Runway and Taxiway Design," by M. A. Warskow, H. P. Galliher, K. G. Grossman, E. N. Hooten, P. H. Stafford, and R. C. Wheeler, Airborne Instruments Lab. Report No. 7601-1, July, 1960.

This paper will present the techniques developed to relate airport operating rate to delay, the factors in airport operations that influence airport capacity, the use of practical applications of the techniques, and some comparative ratings of various configurations. In addition, we will show how the airport operational delay can be evaluated in economic terms, how this evaluation can be used in judging when a project can be justified economically, or which of several possible solutions is the most economical.

FIELD OBSERVATIONS AND MODEL DEVELOPMENT

This project required that mathematical models to accurately relate airport operating rates to the resulting delay be developed, and that the model results be verified through actual field observations. The observations made at sixteen airports have not only given us a thorough understanding of the various details of airport operation, but have permitted us to gather statistical information and data that were used to verify our mathematical models. The models, in concept, accurately represent airport operations. For example, operations on a mixed runway are represented as they normally occur—that is, with arrivals having real life spacing on final approach, arrivals having priority over departures, and departures being released between successive arrivals when a gap occurs that is of adequate length to permit the takeoff. The model predicts the delay to departures that results while the departures await their turn to use the runway. It is not proposed to examine the intricacies of the mathematical models; the referenced report[3] contains a summary of the testing done which shows that the models faithfully represent actual operations.

Several results of the field observations are of particular interest in illustrating the effect of various factors on capacity. For example, we were able to document the "Pressure Factor"—that is, the ability of controllers and pilots to operate more efficiently at higher airport operating rates. Fig. 1 shows the spacing between successive arrivals at various movement rates at different airports; note that the spacing decreases as the operating rate increases. The exception is Wichita, which falls well below the other spacings. Fig. 1 also illustrates that aircraft population has a tremendous effect on airport capacity. The various airports have a similar mixture of commercial and some light or general aviation. Wichita traffic, however, was predominantly light aircraft and, consequently, the spacings were much less.

Observations also indicate that runway length has an effect on the time aircraft spend on the runway during landing. In Fig. 2, the results of observations on the effect of runway length have been plotted, and this factor is used in developing model results. Incidentally, because runway length affects only one out of four model inputs, the effect on runway capacity is not as great as on the spacing factors.

A typical curve was developed with the mathematical models (Fig. 3), to show how average departure delay varies with the operating rate. For this curve we have assumed: (1) a runway layout, (2) an aircraft population, (3) VFR weather, and (4) that arrival rate equals departure rate. The curve in Fig. 3 is a prediction of actual operating results, because it is based on field observations. Similar analyses can be made of other runway and taxiway problems.

It is important to note the meaning of the average departure delay, which is shown on the typical curve in Fig. 3. The departure delay is the average dis-

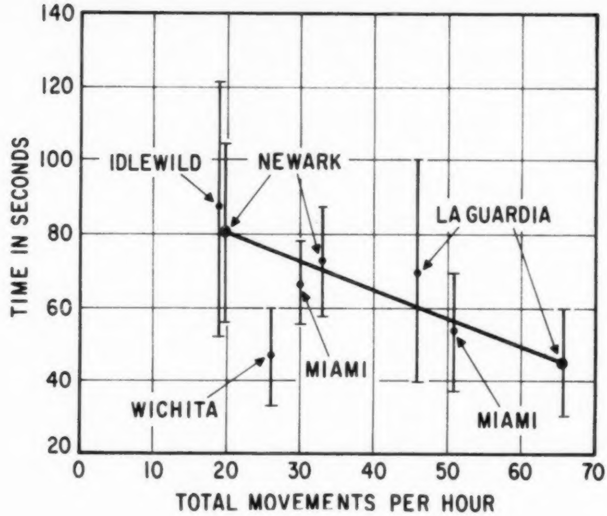

FIG. 1.—VFR SPACING FOR DEPARTURE FOLLOWED BY DEPARTURE

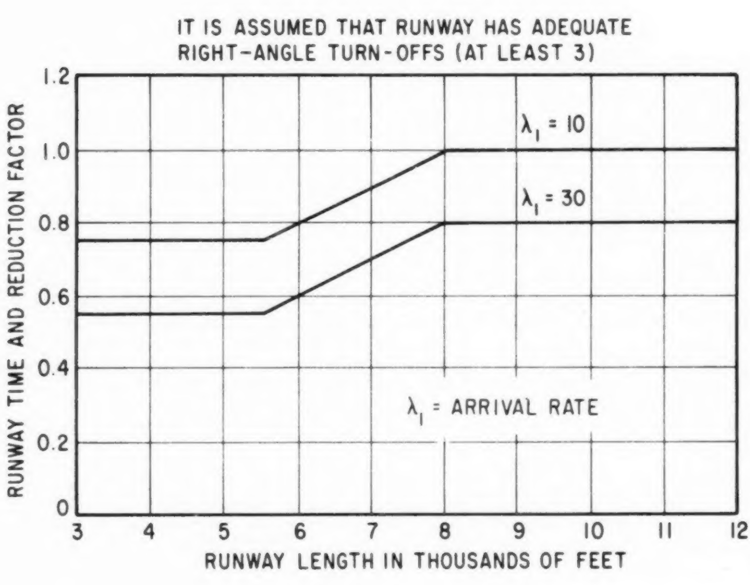

FIG. 2.—EFFECT OF RUNWAY LENGTH AND MOVEMENT RATE

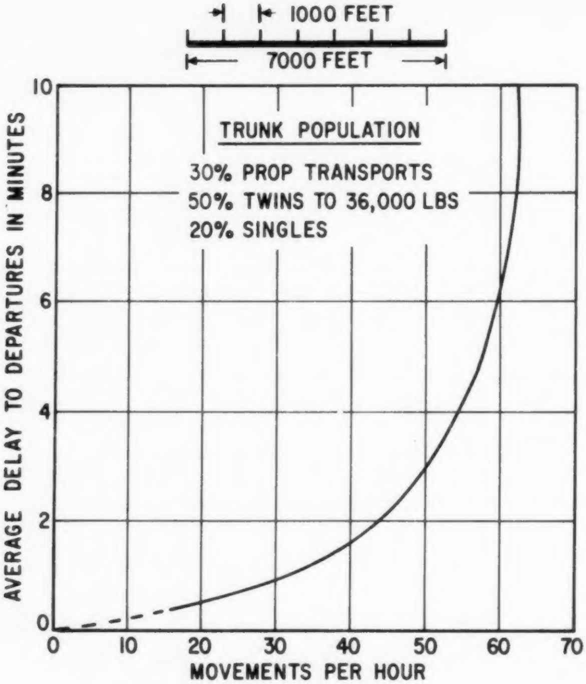

FIG. 3.—CAPACITY OF A SINGLE 7000-FT RUNWAY

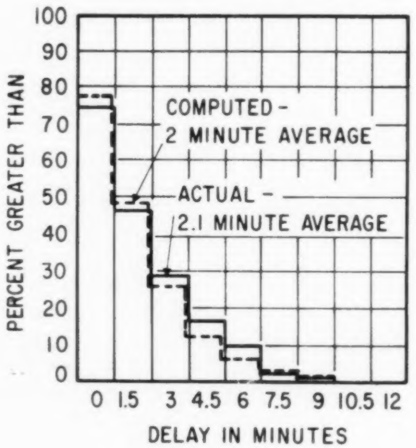

FIG. 4.—DISTRIBUTION OF DELAY—COMPUTED VERSUS ACTUAL

tribution of delays that occur between the time when the pilot calls the tower to advise "I'm ready to go," and the time when the tower advises the pilot, "You are cleared to takeoff." The observed distribution of delay can also be predicted, as shown in Fig. 4. This is a distribution of delay, as observed, and the corresponding theoretical delay distribution. It should be noted that about 20% of the aircraft were not delayed, and that the observed delay distribution is quite similar to the theoretical distribution. Thus, here again, the field observations have been substantiated with mathematical work.

FACTORS AFFECTING AIRPORT CAPACITY

Before selecting a value for the runway capacity, the delay value to be tolerated must be decided. After study of delay distributions and some economic analysis of the value of delay, it was concluded that for many comparisons, a 6-min-average delay is a reasonable value. (In other cases, such as jet aircraft, 4-min-average delay may be the maximum desired delay.) Fig. 5 shows typical distributions for 4-min and 6-min-average delay. Note that with both, maximum delays will be relatively high. A typical runway (Fig. 2) at 6-min-average delay would have a practical capacity of 59 movements per hr.

If this runway were operated at this average rate, it can be expected that the 6-min-average delay will result. The operating rate, however, can also vary around this average rate and still fall within the limits of mathematical techniques. The extent of possible variation in operating rate is shown in Fig. 6. This 10-hr period averages a landing rate of 30 per hr, though there are substantial variations from this average.

FACTORS THAT DETERMINE AIRPORT CAPACITY

The key items in analyzing the capacity of a runway are:

1. Arrival-to-departure ratio;
2. Aircraft population;
3. Runway layout;
4. Weather; and
5. Aerial patterns.

Fig. 7 indicates the effect of varying the arrival-to-departure ratio on a given runway. In this case the higher ratio of departures resulted in the greatest movement rate.

Fig. 8 illustrates the effect of aircraft population. A single 9,000-ft runway with right-angle turn-offs every 1,000 ft was assumed for analysis. The arrival and departure ratio was considered to be unity. The weather is considered VFR, with a standard traffic pattern. Note that the lowest rate results when the greatest number of heavy aircraft is involved. The left curve has no light aircraft and, therefore, the operating rate is relatively low. The center curve has a common distribution of traffic involving all aircraft, from heavy jets to light aircraft. The right curve has no jet aircraft and might represent a situation at the same airport in 1958. Thus, jet aircraft in this case would have reduced airport capacity. This example illustrates the important point that the operating rate attainable on a runway may change, if the aircraft population changes in that time.

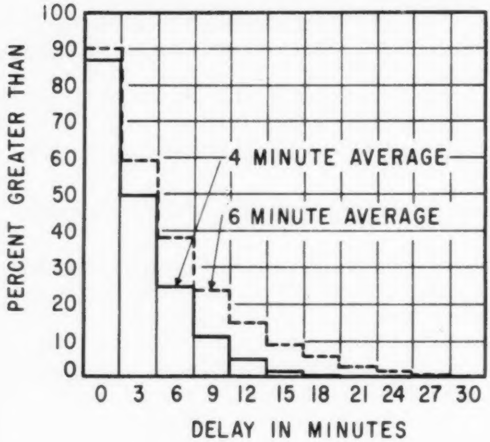

FIG. 5.—TYPICAL DISTRIBUTION FOR 4-MIN AND 6-MIN AVERAGE

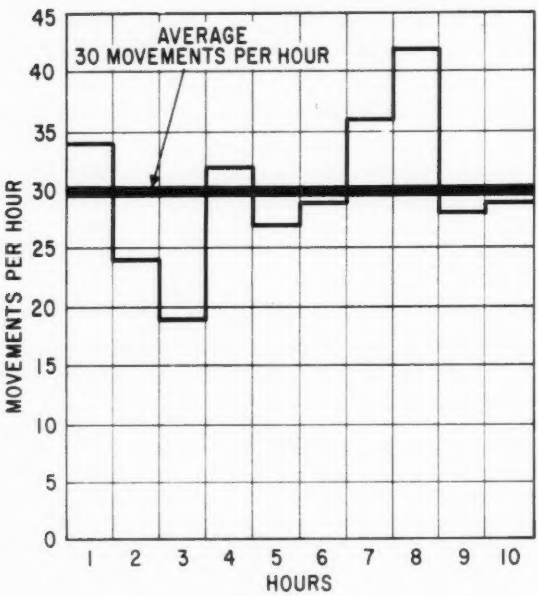

FIG. 6.—TYPICAL FLUCTUATIONS AROUND AVERAGE RATE

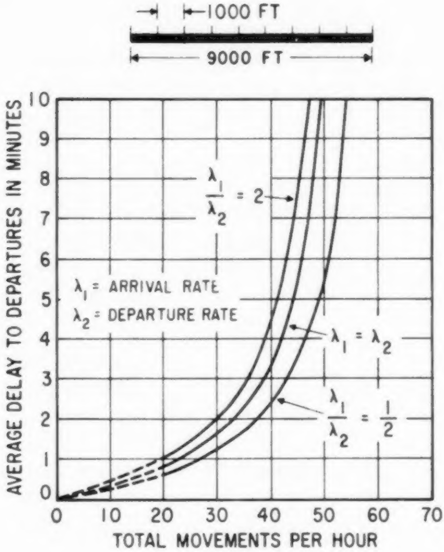

FIG. 7.—EFFECT OF ARRIVAL-TO-DEPARTURE RATIO

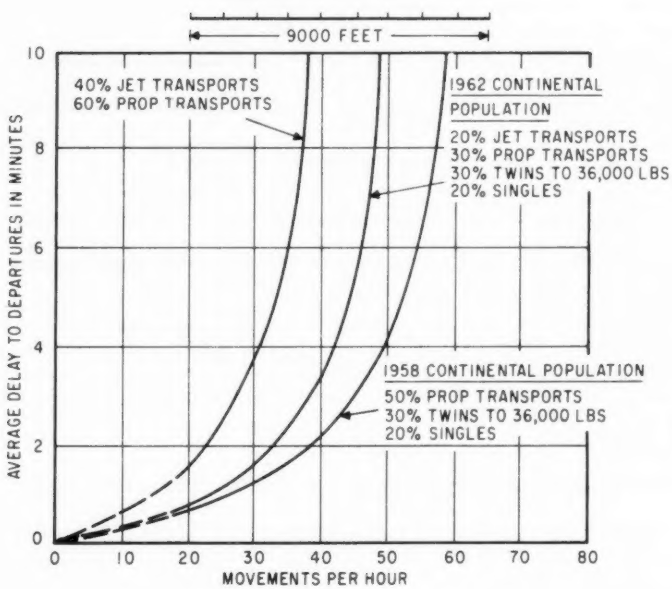

FIG. 8.—EFFECT OF AIRCRAFT POPULATION ON CAPACITY

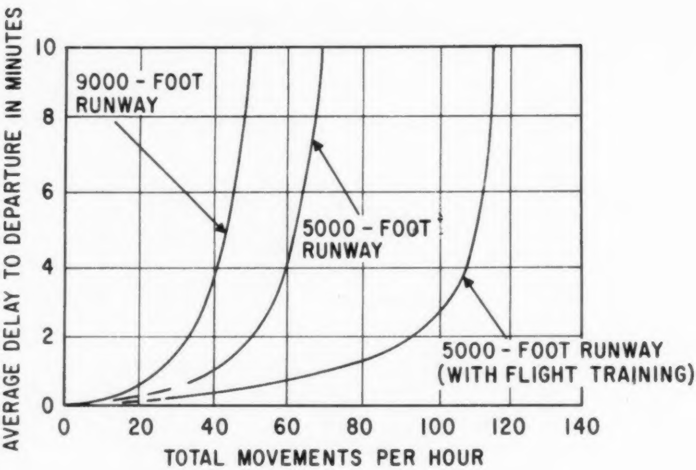

FIG. 9.—VARIATION OF CAPACITY WITH AIRCRAFT POPULATION AND RUNWAY LENGTH

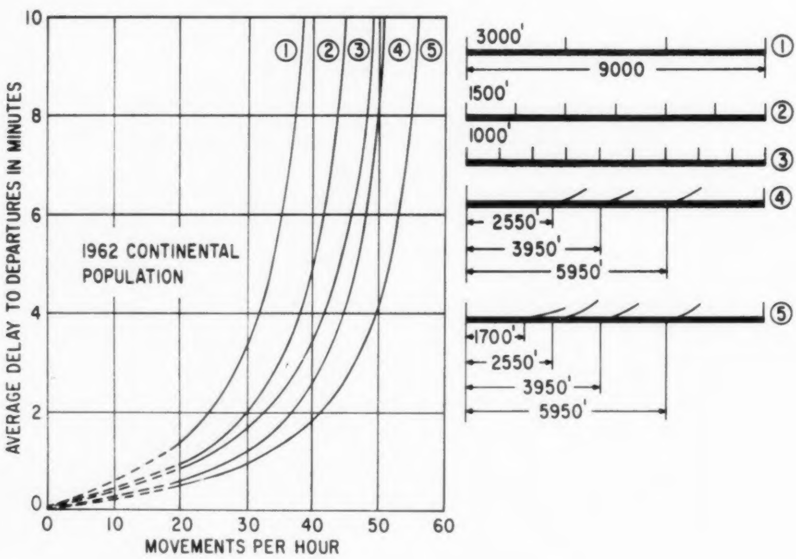

FIG. 10.—EFFECT OF RUNWAY TURN-OFF LAYOUT

Fig. 9 is another illustration of the effect of aircraft population and runway layout. Each of these curves is the operating rate attainable on a single runway. However, the long runway has many heavy aircraft, the center 5,000-ft runway has all general aviation aircraft, and the right 5,000-ft runway, in addition to the general aviation traffic, has a volume of flight training or "touch-and-go" operations. Note that the operating rate for a 6-min delay varies from 35 to 46 to 54 movements per hr.

Fig. 10 indicates the effect of runway layout on capacity. The example shown is for the same 9,000-ft runway (Fig. 8) with the same population but with various turnoff layouts. The top layout, which has a turnoff on 3,000-ft intervals, has a 6-min delay operating rate of 35 movements per hr. This movement rate increases to 53 movements per hr in the bottom layout which has high-speed turnoffs and a light-aircraft turnoff. Thus, the turnoff layout can effect as much as a 50% increase in capacity.

Fig. 11 illustrates the difference between IFR and VFR operations for a given runway. The 6-min delay operating rate in VFR is 66 movements per hr, but in IFR only 38 movements per hr. Thus, in an airport analysis, it is important to look at the VFR and IFR predictions to see which becomes the most critical.

The aerial pattern aircraft follow can also influence capacity. In Fig. 12 the left curve is for the operation of runways 13R and L with all types of aircraft. Because the short runway cannot accept the heavier aircraft, delay on that runway soon builds to the maximum delay value and limits the overall capacity. The center curve is for operation in the 22 direction. To minimize noise problems, however, approaches are required to come in on about the same glide path in VFR and IFR that uses about a 7-mile straight-in approach. This glide path has a very limiting effect on capacity, as is shown by the relatively low rating of this runway combination. The right curve reflects landings on the short 13-31 runway for landing, and departures on the long runway. Thus, depending on the procedures used and the aerial traffic pattern for this airport, the VFR operating rate can vary between 60 movements per hr and 84 movements per hr. Obviously, on some days tremendous delays will result.

FUTURE WORK

The work published in the referenced report[3] includes the data inputs required for VFR analysis. Field work is now (1961) under way to gather similar actual input data for use during IFR weather. In addition, we are now producing a library of operating rate/delay curves, for a variety of runway layouts, aircraft populations, and weather conditions, so that a planner in the field can select a curve that reasonably represents his runway situation. Thus, though the mathematical technique is quite complex, the results will be made available in a form that is readily usable without complex mathematical computations.

RELATIVE CAPACITIES OF DIFFERENT CONFIGURATIONS

The work on configuration analysis is not yet complete. However, an indication of relative capacities is available (Fig. 13). The practical capacities shown are the values selected from operating rate/delay curves when a 6-min-

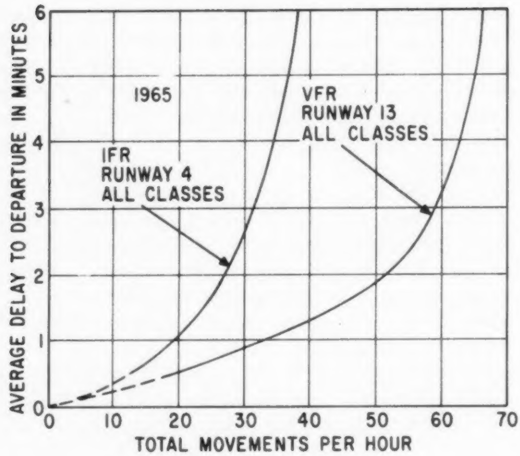

FIG. 11.—VARIATION BETWEEN IFR AND VFR OPERATING RATES

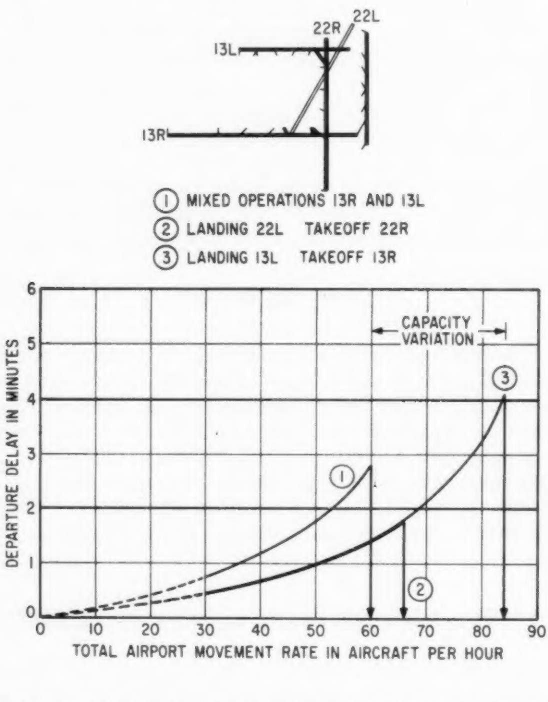

FIG. 12.—VARIATION IN CAPACITY WITH PROCEDURES AND AERIAL PATTERNS

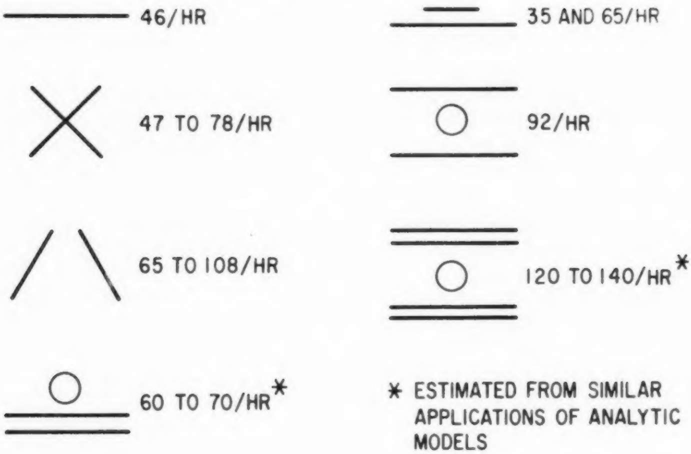

FIG. 13.—RELATIVE OPERATING RATES OF RUNWAY CONFIGURATIONS IN VFR FOR SPECIFIED CONDITIONS (SEE TEXT)

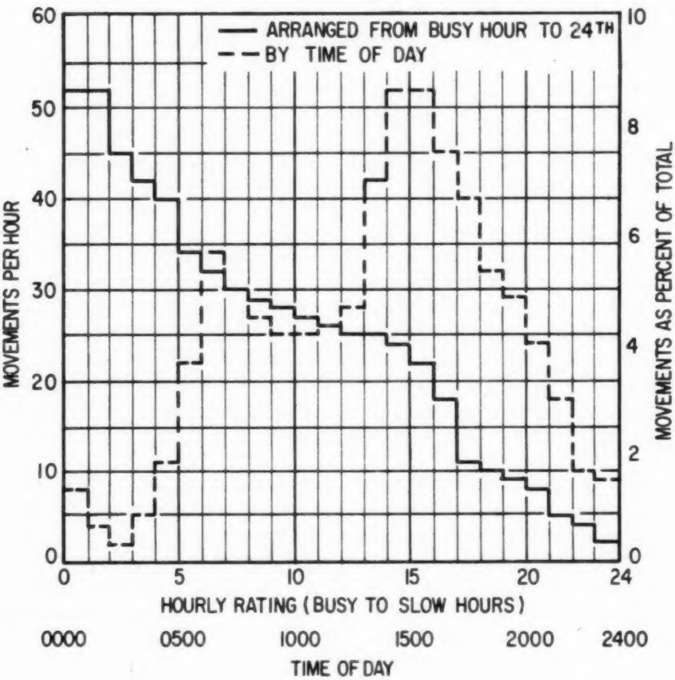

FIG. 14.—TYPICAL HOURLY DISTRIBUTION FOR TOTAL OPERATIONS

average delay is reached. Unless otherwise noted, they are for a 9,000-ft runway with 1,000-ft turnoffs, the continental population used earlier, VFR weather, and equal arrival and departure rates.

The range of movements per hour shown for the intersecting runway layout is due to the location of the intersection with respect to the point of arrival and departure. A higher rate is reached when the intersection points are near the takeoff and arrival end of the runway. Thus, with this layout, the operating rate would vary considerably with wind conditions.

The open-V runway layout operating rate also varies with the direction of the wind, because some coordination must be maintained due to the possibility of crossing centerlines off the airport proper.

The capacity of the close parallel runways is limited by the runway crossing problem, rather than delay due to arrivals and departures on the runway. The delay to crossings can be computed (using the mathematical models) and a practical capacity selected that does not exceed the selected delay either to crossings or departures.

The combination of a short and a long parallel runway shows that the long runway, which accommodates only heavy aircraft in this case, has a capacity of only 35 per hr. The short runway, that would then accept the general aviation aircraft, would have a capacity of 65 per hr. Thus, optimum use of this configuration occurs when the aircraft population consists of about two-thirds light aircraft, that can use the shorter runway.

In the open parallel layout, the practical capacity shown is that obtained by having arrivals on one runway and departures on the other runway.

It appears that the maximum capacity will be attained with an open dual-parallel arrangement. Airspace, however, may become limiting. More research is needed to ascertain whether the airspace can feed a runway layout such as this to capacity.

Thus, there is a tremendous variation in the practical capacity of various airport configurations.

DESIGN BY ECONOMIC ANALYSIS

The development of mathematical models for determining runway capacity and delay has made it possible to measure the performance of airport configurations and to put airport design on a sound economic basis. By comparing the benefit to be obtained and the cost involved, the merit of a proposed airport development can be determined. This is a procedure that is widely used in planning engineering projects such as highways, electric power facilities, and irrigation programs.

The only common denominator for a comparison of airport services and development is money. To determine the economic feasibility of proposed improvements, the value of the services can be estimated and compared with the costs of furnishing facilities.

The optimum design is one that will return the greatest net benefit to the user. Airport user benefits can be evaluated in much the same manner as is done in other comparative economic studies. The relationship of user benefit to cost provides the basis for evaluation. The maximum ratio rather than the maximum net benefit is often considered optimum, but any analysis should consider both. As in other fields of transportation, the comparative economic

evaluation can be used for programming construction from the initial requirement to the ultimate plan. In master planning, the optimum layout for the ultimate use should be developed and stages of construction defined for optimum return at various steps in traffic growth. Projects with a benefit-cost ratio of less than one should not be undertaken, and the projects with the highest ratio should be given priority for construction.

In all cases, design standards for runway length, width, lighting equipment, and approaches must be followed to assure proper safety. User benefits are measured by comparative operating costs. Any change that reduces aircraft delay or operating time will result in a definite saving to the operator.

Concern has often been expressed about the apparent fact that airport improvements are generally financed by public agencies and the benefits are reaped by the airport users. As in other similar public works projects, the savings can be paid to the airport owner in fees to cover the costs of improvements. This is now done at many airports. The surplus, and any indirect benefits, are distributed by natural economic processes to the owner of the airport, aircraft operators, passengers, airport customers, and the general public.

If the airport site has not been selected, preliminary studies for a particular location include an economic analysis of the major factors that affect site selection. Economic analysis of user benefits for the ground transportation access to the airport is one important study that can be included. User benefits to be considered in this study, as in highway benefit-cost analysis, can include direct transportation costs plus time savings for the individual passengers. Indirect benefits may include greater usage of the airport and its related facilities.

Airport development and operations can be restricted at specific locations by the topography of the site, the topography of the approaches or turning areas, and the limitation of usable airspace by other airports. Noise abatement is a current but, hopefully, temporary airspace problem that should be corrected by means other than limitations on airspace usage.

Site limitation may dictate a less efficient layout, such as intersecting runways, closely spaced parallel runways, or less efficient placement of the terminal area. Restricted approaches are usually more important in instrument operations where certain approaches are unusable or where turns are restricted. Many sites will have combinations of topography and airspace restrictions.

Ideally, a site with restrictions should not be selected, because this lowers the efficiency of operations. However, the optimum airport for a particular location may accept certain inefficiencies to avoid excessive development costs or an unreasonable ground travel distance. The effect of restrictions and the cost of reducing the extent of limitations must be fully explored by economic analysis.

The standards of design, the consideration of any surface restrictions, and the determination of a preliminary runway layout will provide the initial typical configurations for which an economic evaluation can be made. The optimum design is then determined by the economic analysis of the factors that affect airport operations.

The curves developed from the mathematical models can be used to determine anticipated delays caused by runway operations. In other aircraft operations on the airport (excluding terminal servicing), taxi routes and taxi speeds will determine the extent of delay.

Taxiing times can be computed by using average speeds for different sections and average delays for points of conflict. Preliminary studies such as the examples shown in this paper can be based on weighted average figures. A more exact analysis can be made of a specific configuration if the respective portions that make up the aircraft population are handled separately in all computations. To obtain a more accurate analysis, we can make use of exit taxiways selected by aircraft type, taxi time at average taxi speeds of each aircraft type, and probable assigned gate position, or other destination.

User benefits in these analyses are measured by estimated savings in aircraft operating costs. The values presented in Table 1 and used in the examples that follow were developed from data recently reported to the Civil Aeronautics Board by the various airlines.

The appropriate data can be properly weighted by types of aircraft for the airport population at a specific time to determine aircraft operating cost per minute for an airport.

Aircraft population is one of the basic factors that affect airport design and must be forecast through the period of study. Ordinarily, this population cannot be controlled except through the provision of other airports, and it is a result of customer demands for various airport services. Forecasting is very important, but obviously it cannot be completely accurate because of unexpected

TABLE 1.—SELECTED AIRCRAFT OPERATING COSTS

Aircraft Type	Class	Cost per Minute
Boeing 707, Douglas DC-8	A	$15.00
Four-engine, propeller	B	6.00
Twin-engine, transport	C	3.00
Twin-engine, executive	D	1.00
Single engine	E	0.25

technological developments and changing economic conditions. It is not necessary to divide the population into a great number of aircraft types. Four to six categories should be sufficient to estimate airport performance and permit reasonable forecasting by categories. The populations given in the Tables 2 and 3 will be used for the examples of studies for optimum design. The actual or projected population should be used to study any specific location.

Scheduled air carrier traffic is quite uniform with a typical hourly pattern repeating daily. The peaks vary in number and in time depending on the type of traffic and the flight times to principal intermediate points or to final destinations. Generally, the periods of high activity for light aircraft and air carrier transports are the same, but the peak hours do not coincide. It has been found that when the hourly rates are plotted in order of magnitude, the patterns are very uniform (Fig. 14 and 15). For reasonably high volumes there is a straight-line distribution of air carrier traffic with a maximum of 8% to 10% of daily operation in the busy hour; at airports with less than 100,000 movements, the traffic is more concentrated over a shorter period. The distribution has a great effect on the delays from landings and take-offs, but has much less effect on time used for long taxi routes and for taxiway intersections.

To simplify computations, the "design day" for scheduled traffic may be taken as an approximate straight-line distribution over 13 hr, 19 hr, or 24 hr, with a maximum of 16%, 10%, or 8% in the highest hour and handling 1/360 of

TABLE 2.—AIRPORT POPULATION

Airport	Suggested 1962 Population by Class, in %				
	A	B	C	D	E
Intercontinental	40	30	10	10	10
Continental	20	30	20	10	20
Trunk	0	30	30	20	20
Local	0	0	30	20	50

TABLE 3.—OPERATING COSTS FOR SUGGESTED POPULATIONS

Airport	Aircraft Class	Cost	Percentage	Total per Minute
Intercontinental	A	$15.00	40	$6.00
	B	6.00	30	1.80
	C	3.00	10	0.30
	D	1.00	10	0.10
	E	0.25	10	0.03
		Total	100	$8.23
Continental	A	$15.00	20	$3.00
	B	6.00	30	1.80
	C	3.00	20	0.60
	D	1.00	10	0.10
	E	0.25	20	0.05
		Total	100	$5.55
Trunk	B	$ 6.00	20	$1.20
	C	3.00	30	0.90
	D	1.00	20	0.20
	E	0.25	30	0.08
		Total	100	$2.38
Local	C	$ 3.00	30	$0.90
	D	1.00	20	0.20
	E	0.25	50	0.13
		Total	100	$1.23

the annual traffic. Where traffic records are available, modifications can be made to conform to the average daily distribution.

The distribution is much more variable for general aviation than for scheduled aircraft. A logical assumption for the design day is a 10-hr straight-line distribution with a 20% daily peak and based on 1/300 of the annual movements.

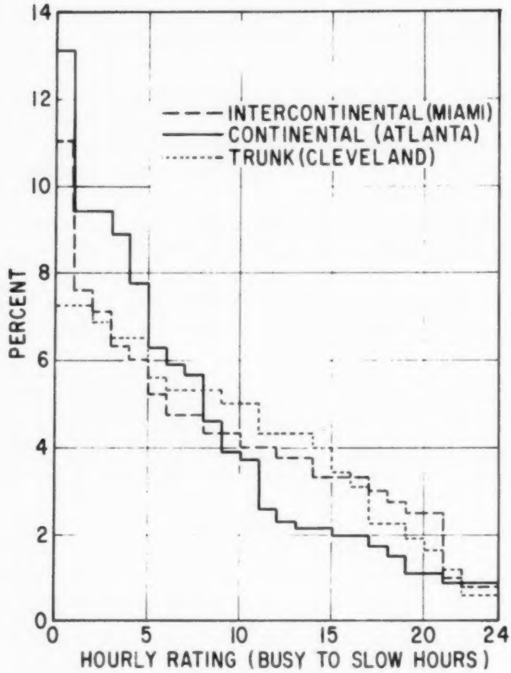

FIG. 15.—HOURLY DISTRIBUTION OF AIR CARRIER MOVEMENTS BY PERCENTAGE

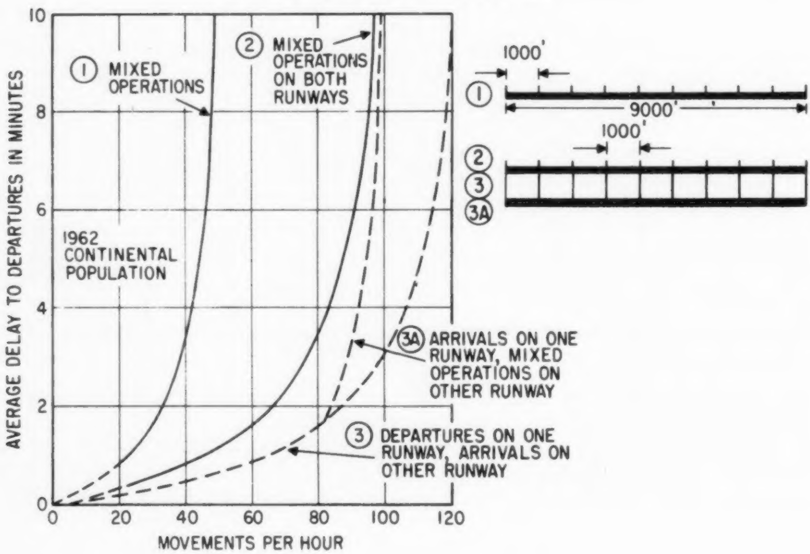

FIG. 16.—ANALYSIS OF PARALLEL RUNWAY USE

General aviation aircraft are largely operated under Visual Flight Rules and can be considered only for a VFR design day.

Typical distributions of traffic in order of magnitude are given in Table 4 by percentage of design-day volume.

The percentage of aircraft exiting at individual taxiways is another factor to be considered in optimized design. This data establishes the taxi routes taken by the various aircraft.

Taxi speeds are assumedas normal maximum speeds. These speeds were determined by field observations. The major factor in taxi speed is the length of the section of taxiway between turns or intersections. In the economic analysis the following data were used

TABLE 4.—TYPICAL TRAFFIC DISTRIBUTIONS BY HOURS IN PERCENTAGE

Hour	Low	Air Carrier Medium	High	General Aviation All Airports
1	16	10	8	20
2, 3	12	9	8	16
4, 5	10	8	7	11
6, 7	8	7	6	7
8, 9	6	6	5	4
10, 11	4	5	4	2
12, 13	2	4	3	0
14, 15	0	3	3	0
16, 17	0	2	3	0
18, 19	0	1	2	0
20, 21	0	0	2	0
22, 23, 24	0	0	2	0

Average taxi speeds for various straight distances:

Distance, in Ft	Speed, in Ft Per Second
0 to 1000	25
1000 to 1500	30
1500 to 2000	40
2000 to 2500	50
over 2500	60

Maximum taxi speeds for various aircraft:

Aircraft Class	Speed in Ft Per Second
A	60
B	60
C	60
D	50
E	40

Construction, amortization, and maintenance costs can be estimated with a degree of accuracy consistent with the purpose of this study. Only basic cost factors have been considered:

Item	Cost in Dollars Per Sq. Yd.
Pavement, lighting, etc.	8.00
Intercontinental	7.00
Continental	6.00
Trunk	5.00
Local	
Grading, drainage, etc.	
All airports	2.00

Annual cost of construction, including amortization of capital expenditure, is assumed to be 1/15 of the total cost of construction. Annual cost of maintenance, including repairs and replacement, is also assumed to be 1/15 of the total cost of construction. Total annual cost is, therefore, 2/15 of the total cost of construction.

TABLE 5.—DIFFERENCE IN DELAY

Hour	Movements		Total	Saving in Departure Delay, in Seconds	Saving per per Day, in Seconds
	Air Carrier 70% = 140	General Aviation 30% = 60			
Busy	14.0	12.0	26.0	60	780
2	12.6	9.6	22.2	44	985
4	11.2	6.6	17.8	32	570
6	9.8	4.2	14.0	24	336
8	8.4	2.4	10.8	18	194
10	7.0	1.2	8.2	12	98
12	5.6	0	5.6	8	45
14	4.2	-	-	6	25
16	2.8	-	-	4	14
18	1.4	-	-	2	3
20	0	-	-	-	-
				Total	3050

$\frac{3050 \times 300}{60}$ = 15,300 min per yr, considering only the VFR days

Parallel Runway at Continental Airport.—An example of benefit-cost analysis is determining the stage in airport development at which additional runways are warranted by the increasing traffic. For example, the initial construction for a continental airport (with a single 9,000 ft by 150 ft runway, parallel taxiway, exit taxiways every 1,000 ft, and terminal apron areas) would be adequate for a practical operating rate of 46 movements per hr.

To increase the capacity of the airport beyond 46 movements per hr at the anticipated 6-min-average departure delay, it would be necessary to begin the

second phase of construction. Phase II construction might include addition of a parallel runway system with parallel taxiways, exit turn-offs and connecting taxiways to the terminal.

Phase II construction costs would be:

Cost of construction $4,145,000
Annual cost of construction 276,000
Annual cost of maintenance 276,000
Total annual cost 552,000

In determining the break-even volume of Phase II construction, consider the completed runway-taxiway system. The change in delay for each number of movements per hour can be determined as the difference between the operat-

TABLE 6.—RUNWAY UTILIZATION

Runways Used	Runway Direction		Utilization, in %
	Landing	Take-off	
Combination A	12	1	35
Combination B	19	30	20
Combination C	30	1	15
Combination D	1	30	5
Single runway	12	12	10
Single runway	30	30	5
Single runway	1	1	5
Single runway	19	19	5

TABLE 7.—PERCENTAGE OF AIRCRAFT USING VARIOUS EXITS

Landing Runway	Exit Number					
	1	2	3	4	5	6
12-30, 30-12	0	10	30	30	20	10
19-1	0	20	30	40	10	-
1-19	0	10	40	40	10	-

ing rate/delay curves (Fig. 16) for single and parallel runways. The previously discussed factors of time distribution of traffic, typical population, percentage of aircraft exiting at various turn-offs, and cost data are all considered. Table 5 shows the difference in delay for the single and parallel runway layouts and the time saved after completion of Phase II construction. (Design day assumed to be 200 movements per day.)

The percentages of aircraft exiting from the landing runway at various exits from the threshold are estimated in Table 7 from exit performance data.

Table 1 is a sample computation of taxi time and taxi time saved for landing runway 12-30.

By similar computation, other design days will show saving in time as follows:

Movements Per Day (Assumed)	Minutes Per Yr
300	48,600
350	90,800
375	134,600

To break even the saving must be $552,000—the total annual cost of the improvement. The cost per minute for this population is $5.55. Minutes saved

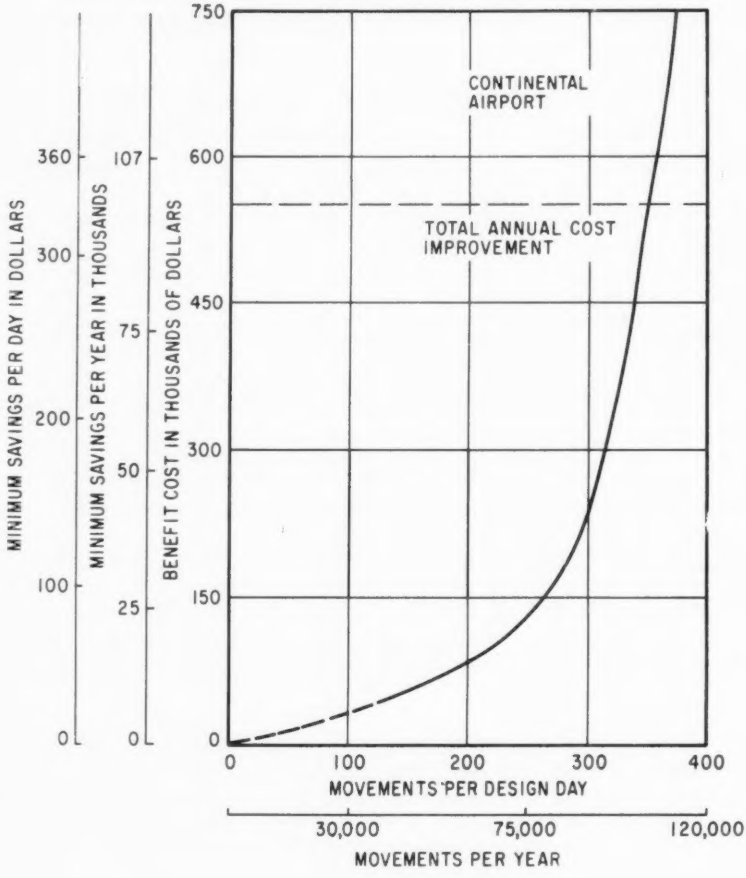

FIG. 17.—BENEFIT-COST ANALYSIS OF PARALLEL RUNWAYS

per year to break even would equal 552,000 ÷ 5.55 = 99,600 min. This relation is shown in Fig. 17, which indicates the intersection of the curve for the total annual cost. The curve is drawn through various points determined by

the annual benefit representing the time saving to the aircraft operators. The break-even volume in Fig. 17 is thus 352 movements per design day. This represents a total annual operation of 105,600 movements.

This method of analysis is equally applicable to other airport layouts. With the appropriate assignment of values and addition of other factors under consideration, the analyses can be extended to cover any airport configuration.

Terminal Relocation at Trunk Airport.—A further example demonstrates how the cost of taxiing affects the economic evaluation of terminal relocation at a trunk airport (Fig. 18). The object is to determine if it is economical to relocate the airport terminal, and to find the break-even traffic volume. The economics of the new terminal area are excluded, and only taxiway development

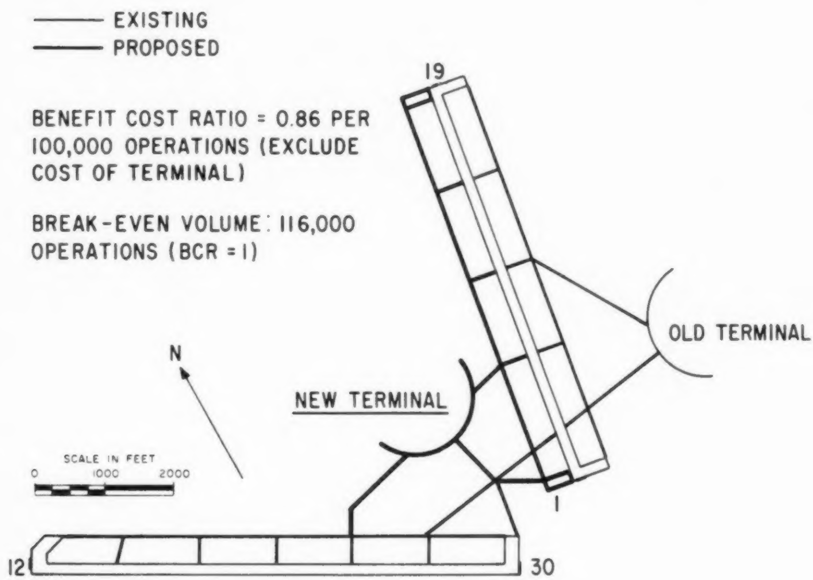

FIG. 18.—TERMINAL RELOCATION OF COMPOSITE AIRPORT TRUNK

and operation savings in aircraft taxiing are considered, as well as average taxi speeds, taxiway and runway crossing delays, population, and construction costs. The percentage utilization of runways is estimated in Table 6.

On the basis of the data in Table 8, the total saving in taxi time for aircraft landing on runway 12-30 can be determined, as shown in Table 9.

Table 10 gives the total savings in taxi time for all aircraft operations at the airport for all runways.

The user benefit or operating saving can be determined by multiplying the average time saved per operation by the cost per minute, which is \$2.38 for the suggested trunk population. The average saving per operation is

$$\frac{40.25}{60} \times \$2.38 = \$1.60$$

TABLE 8.—TAXI TIME SAVED FOR LANDING RUNWAY 12-30

Exit	Old Taxi Time			New Taxi Time		
	(feet)	(fps)	(seconds)	(feet)	(fps)	(seconds)
2	500	25	20	-	-	20
	3000	60	50	2000	40	50
	300 (turn)	30	10	300	25	12
	2000	40	50	300 (turn)	30	10
	Runway	Delay	25	-	-	-
	400	25	16	-	-	-
	Taxiway	Delay	5	-	-	-
	1300	40	32	1300	40	32
			208			124
	Saving: 84 sec (10%)					
3	-3000	60	-50	-2000	40	-50
	+2000	40	+50	+1000	25	+40
			208			-10
						114
	Saving: 94 sec (30%)					
4	-2000	40	-50	-1000	25	-40
	+1000	25	+40	Taxiway	Delay	+5
			-10			-35
			198			69
	Saving: 129 sec (30%)					
5	Recalculate		20	-	-	20
	2000	40	50	1200	25	48
	Runway		25	-	-	-
	400	25	16	-	-	-
	Taxiway		5	-	-	5
	1300	40	32	800	25	32
			148			105
	Saving: 43 sec (20%)					
6	End		20	-	-	20
	800	25	32	-	-	32
	Taxiway		5	-	-	5
	1000	25	40	-	-	-
	Runway		25	-	-	-
	400	25	16	-	-	-
	Taxiway		5	-	-	-
	1300	40	32	-	-	32
			175			89
	Saving: 86 sec (10%)					

A summary of the costs of the new taxiways, holding aprons, and so forth, exclusive of the terminal area development, is as follows:

Cost of construction of parallel
taxiway for runway 10-19. . . . . $685,000

Cost of construction of connecting
taxiway for runway 10-19 to
new terminal area $492,000

Cost of construction of connecting taxiway for runway 12-30 to new terminal area $210,000

Total cost of construction, excluding new terminal area (building, gate positions, ramp). $1,387,000

Annual cost of construction $93,000

Annual cost of maintenance $93,000

Total annual cost $186,000

On the basis of this data and the taxi time savings, the break-even volume is

$$\frac{186,000}{1.60} = 116,000 \text{ operations per yr.}$$

Multiple runways increase capacity and reduce delays only when two or more are used concurrently. If a number of runways that only permit operations into the wind are used separately, then the greater the number of runways, the more delays that will be occasioned by changing traffic from one runway to another. This can also become a serious matter if the runways are unequal in length or

TABLE 9.—TAXI TIME SAVING

Exit	Time in seconds	Time in percentage	Saving, in seconds
2	84	10	8.4
3	94	30	28.2
4	129	30	38.7
5	43	20	8.6
6 (end)	86	10	8.6
			92.5

TABLE 10.—TOTAL SAVINGS IN TAXI TIME

Runway Preference	Utilization, in %	Savings in Seconds: Landing aircraft	Savings in Seconds: Landing total	Aircraft Take-Off	Take-Off Total
Combination A	35	92	32.2	-16	-5.6
Combination B	20	10	2.0	65	13.0
Combination C	15	83	12.5	-16	-2.4
Combination D	5	10	0.5	65	3.3
Single Runway 12-30	10	92	9.2	82	8.2
Single Runway 30-12	5	83	4.1	65	3.3
Single Runway 10-19	5	10	0.5	-16	-0.8
Single Runway 19-10	5	10	0.5	1	-
Average delay in seconds			61.5		19.0

Average delay per operation $= \frac{61.5 + 19.0}{2} = 40.25$ sec

differ in approach conditions because pilots may request a runway other than the one currently in use. This will tend to cause delays. Situations may arise at an airport limited to a single runway when certain traffic, particularly light aircraft, are restricted from operating. This is not as substantial as it might appear, for high wind conditions will frequently ground such operations though a number of runway directions are available.

A second runway direction can show a direct benefit in proportion to the additional traffic that could not use the primary runway. A secondary benefit may result from improved reliability of service. Because this additional traffic will normally be only 1% to 5% of the total, and because the airport is often closed for a much greater time for other weather conditions, this secondary benefit should not exceed the direct benefit.

To compute the benefit of a cross runway, the percentage of additional traffic by types should be determined and doubled to include indirect benefits. The benefit will be a percentage of the income of the airport. It may also be assumed that if such a runway increases utilization by 5%, this will justify a capital expenditure of 10% of the total airport development cost. If such a cross runway can make savings in operational times, these savings should also be included as benefits. It must be remembered that the simultaneous use of two runways is undesirable without a traffic control tower.

CONCLUSIONS

1. Techniques using mathematical models have been developed to accurately analyze airport layouts by relating operating rates to the resulting delays.
2. The most important factors to be determined in analyzing airport capacity are the arrival-to-departure ratio, the aircraft population, the runway(s) layout, the weather during the operation, and aerial patterns.
3. By use of aircraft delay data and other measures of benefits, an economic analysis of any airport improvement can be made.
4. The benefit-cost method of analysis can give objective, quantitative comparisons for use in determining site selection, airport configurations, and staged development programs.
5. This method does not eliminate the need for a thorough study of all factors by competent people with imagination and ingenuity in developing solutions for analysis.

DISCUSSION[a]

R. J. SUTHERLAND,[4] F. ASCE.—Certain figures were cited for operating costs of airplanes - $900 per hr. Other figures give more definition of what a delay will cost an airline. The value of $900 per hr is for direct operating cost and only covers fuel costs and crew salaries. The earning capacity of the

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[a] The full discussion from the floor was taped recorded, but for the sake of clarity and brevity the remarks were slightly condensed and, occasionally, paraphrased. In some cases the identity of the discusser could not be determined.

[4] Airport Engr., American Airlines, New York, N. Y.

707 is approximately $2,000 per hr. Depreciation on the airplane is approximately $100 per hr, so if you add the $900 to the $2,000, and $100 for depreciation, there results $3,000 per hr for loss due to delays. Let's assume one 707 is scheduled to operate two round trips a day from New York to Chicago; also let's assume there's an average delay at both ends of the line of 15 min. That's a total delay of 1 hr for that particular airplane for two round trips a day, or $3,000 a day the airplane is losing. Now, that means if an airline has to produce a certain number of passenger miles a year it has to have more airplanes to do it. In turn, it has to have more crews which have to be trained; this means more training facilities. The airlines have to have more hangars to support those airplanes, so all in all these costs can mount up terrifically. These figures should point out to the airport operators and the engineers what improved operating efficiencies can do for airlines.

FROM THE FLOOR.—Noting that the figures used by Warskow and Stafford were in terms of delays with departing aircraft and the cost engendered by these departure delays, one wonders what consideration has been given to the problem of delays encountered by arriving aircraft.

RESPONSE.—The analysis technique described herein can be used to predict arrival delay as well as departure delay. Arrival delay caused by the airport runway layout itself is not large and has been assumed at 2 min for VFR (visual flight rules) conditions and 3 min for IFR (instrument flight rules). The arrival delay in the air, before the aircraft reaches the airport proper, is harder to measure.

FROM THE FLOOR.—The figures showed delay plotted against movements per hour, with a certain amount of delay shown for as little as 2 movements per hr or 3 movements per hr (arrivals and departures). Can this be explained further?

RESPONSE.—With an uncontrolled system, as is the case in VFR conditions, even though only two aircraft arrive in one hour, both might choose to arrive at the same time, so one must necessarily encounter a slight delay.

Journal of the

AIR TRANSPORT DIVISION

Proceedings of the American Society of Civil Engineers

NEW DEVELOPMENTS IN TERMINAL AIR TRAFFIC CONTROL

By Walter N. Pike[1]

SYNOPSIS

Studies are being made to develop a comprehensive program of inter-related projects that will deal with the air traffic control problem on a total system basis. Recently developed equipment is described, and illustrations as to its use are presented.

Terminal area operations have long been recognized by the FAA as one of the most critical problem areas of air traffic control and as such, have been given top priority in the implementation of many modern aids. The full effect of many of these implementation programs is yet to be felt, but many engineers are aware of the rapid progress being made by other FAA Bureaus as they commission new instrument landing systems, airport surveillance radars, airport surface detection equipment (AS DE radar) as well as the vortac system of navigational aids. In the near future we will begin to see the results of programs for implementation of the Air Traffic Control Radar Beacon System and scan converted bright radar displays. In the field of research and development, and particularly in the field of automation, one may have gained the impression that primary emphasis was being placed on enroute type functions. This is true to a limited extent and only because these functions are basic to overall systems operation.

Note.—Discussion open until January 1, 1962. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Air Transport Division, Proceedings of the American Society of Civil Engineers, Vol. 87, No. AT 2, August, 1961.

1 Chf., Data Processing and Display Branch, Development Div., Bur. of Research and Development, Federal Aviation Agency, Washington, D. C.

Other papers in this Symposium will deal with the intricacies of airport design and construction as well as the visual-aids programs. This paper will, therefore, be confined primarily to the area of equipment systems of electronic hardware for automating the basic air traffic control functions. These systems both increase and decrease the terminal airport problem at the same time. First by making it easier to rapidly move aircraft from one terminal facility to another and, second, by arranging this expedited flow in an orderly manner so as to make maximum use of the terminal airport capacity.

Some interesting facets of the terminal air traffic problem are illustrated in Fig. 1 which shows the ten high density terminal areas in the United States ranked by total operations in 1960. The operations of take-off landing and low approach are summed for all airports within the 50-mile radius of the major terminal. In 1960, these ten areas accounted for 22.6% of the total operations.

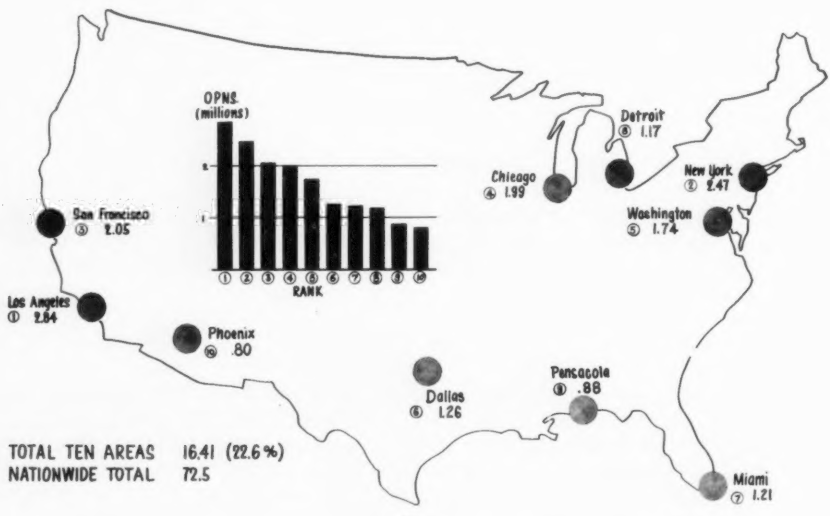

FIG. 1.—HIGH-DENSITY TERMINAL OPERATIONS RANKED BY MILLIONS OF TOTAL OPERATIONS IN 1960

In the next ten years operations of these hubs are expected to increase by about 45% whereas nationwide only a 25% increase is anticipated. A particularly significant fact is that general aviation already accounting for 44 million out of 62 million busy day operations in these ten areas will, by 1970, be accounting for 74.4 out of 90.2 million operations, an increase of 70%. The nationwide increase in general aviation in the same period will approximate 52%, whereas the total operations will have only increased by 25%. Future traffic control, therefore, appears to need to be more in terms of the general aviation user rather than the trained and disciplined military and air carrier pilot. The aids and procedures must take into account the relative infrequency of operations on the part of this class of user as contrasted to the almost daily experience of the commercial and military classes.

To tackle the ATC problem on a total system basis we have had underway for some time an intensive development program including projects for airport runway lighting, high-speed turnoffs, visual landing aids, improved electronic landing aids and navigational facilities, three-dimensional terminal area radar, advanced ATC radar beacon video processing and display equipment, and the complete semi-automatic air traffic control data processing and display sub-system known as the Data Processing Central. This latter element applies principles of automation to relieve the air traffic controller of a majority of his routine manual computation and coordination duties, leaving him free to concentrate on the important decision-making functions.

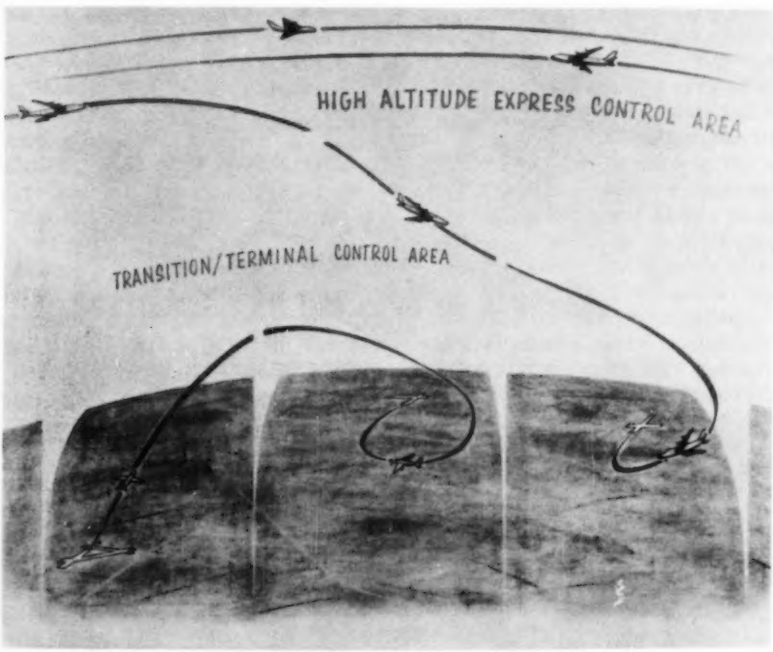

FIG. 2.—HIGH ALTITUDE—TRANSITION/TERMINAL CONTROL CONCEPT

The operational concept to which we are progressing with the DPC subsystem is illustrated in Fig. 2. Under this concept, the high-altitude control areas above flight level 24 are handled on an area-control basis with positive flight following. This area in particular is under consideration for joint military/civil coverage using the SAGE facilities. Additionally, consideration is being given to lowering the base of this coverage to about 14,000 ft. Under the present day concepts, however, the basic operations are divided into those of enroute or peripheral control and transition terminal. With the former principally ANC time and altitude separation and the latter heavily dependent on radar control.

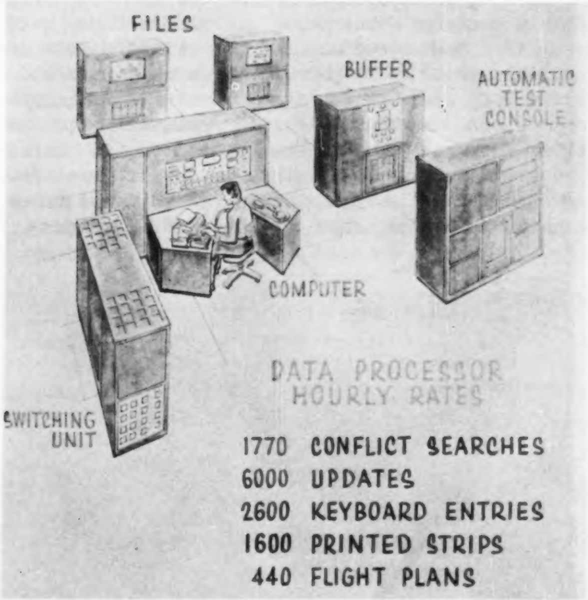

FIG. 3.—SYSTEM MODERNIZATION

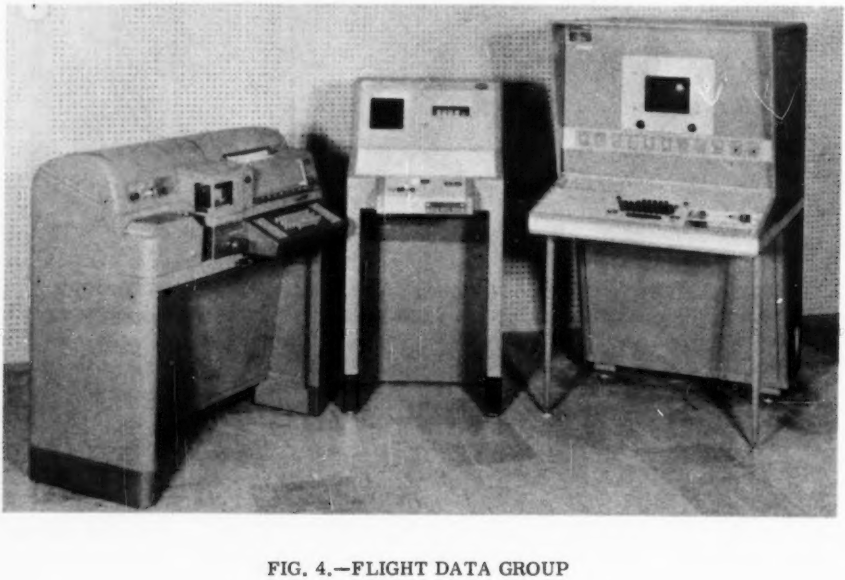

FIG. 4.—FLIGHT DATA GROUP

Functionally the system has been divided into ten basic groupings. Noted previously, our assumed pre-occupation with those that are characteristic of enroute operation has been because these are basic to all operations. Function No. 1, for example, is Flight Plan Acceptance, Processing and Distribution throughout the system. The heart of this function and all other functions is a digital Data Processor consisting of a computer, drum files for flight plan and other storage, input-output buffer, and file duplexer and computer switching units. The basic elements are illustrated in Fig. 3. In systems operation, the flight plans are initially filed via teletype telephone from the operations offices and transmitted to the Flight Plan Group, shown in Fig. 4. In Fig. 4 the Model 28 ASR teletypewriter is shown and on the right is the FLIDEN flight data entry equipment. The center unit is a Flight Plan Disposition unit from which the controller takes final action on disposition of any messages found to be in error. On entry of the flight plan, it is stored in the computer until a pre-determined time before take-off. At this time it is called into active service, broken down by air route segments with estimated times of arrival computations made for the initial fixes, and flight progress strips printed at each operating position. These strips are prepared by the Punch and Printer illustrated in Fig. 5. They are then manually loaded into strip-holders by the controller and inserted in the Peripheral Sector Console under the appropriate Fix Header strip. In Fig. 6 the initial model of the Peripheral Sector Console with the moving print head, data entry keyboards and pictorial conflict display is shown. As flight plan changes occur, actual times of arrival are recorded, or other changes affecting flight progress are made they are reported to the responsible controller who makes appropriate data entries. Both initially and at any time a change is made, the system searches on a route segment basis for possible conflicts. Should such be detected, the warning light appears on the pictorial conflict display. The operator then can call up pertinent information relating to the present location of the aircraft and fix over which the conflict will occur. This information appears as shown in Fig. 7. Additionally, warning lights appear alongside the flight progress strips of the aircraft involved.

One of the principal advantages gained through automation is automatic coordination between the various sectors and between centers. For example, at the present time when the correction to a flight plan is made, manual entries must be made on an average of five flight progress strips. With automation, and a single entry, the computations and corrections will be made for each posting and these entries automatically made. A warning light will advise the controller that a correction has been made. Fig. 8 illustrates an improved version of the Automatic Up-dating Console that scheduled for implementation. The fourth function of the system is bright radar display with hand-off symbols that will be discussed subsequently. The fifth function is the last of the enroute functions, but one that bears heavily on the transition terminal area. This is flow-control. It is to be accomplished using statistical data in the computer, weather information, and the Flow-Control Console shown in Fig. 9. Operational concepts for this function have not yet been fully worked out but, basically, it provides data on the terminal acceptance rate for up to five terminals in an area. It shows the total traffic expected, the total traffic ordered, the predicted delay and critical delay and will permit holding of traffic outside the congested transition terminal area on an orderly and equitable basis.

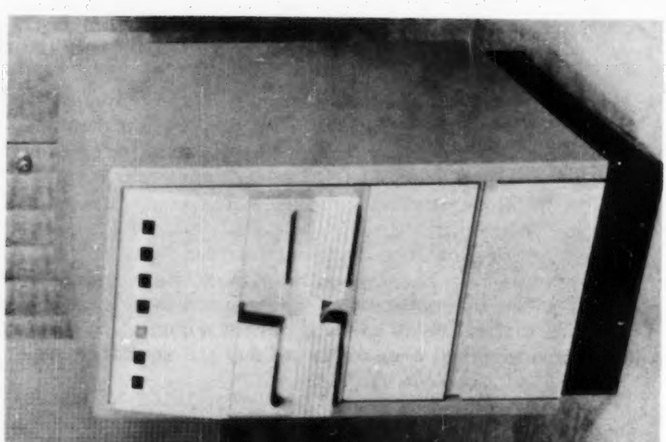

FIG. 5.—PUNCH AND PRINTER

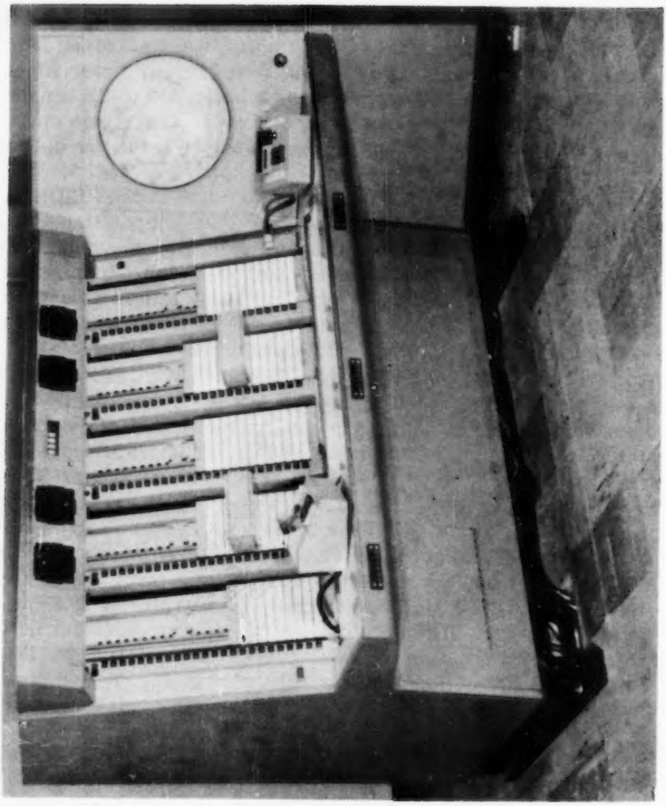

FIG. 6.—PERIPHERAL SECTOR CONSOLE

The functions of the transition/terminal area are heavily dependent on good radar coverage. A notable development in this regard that is nearing successful completion is the three-dimentional or Airport Height Surveillance Radar. As shown in Fig. 10, this system utilizes existing terminal area surveillance radar such as the ASR-2 or ASR-4 to illuminate the aircraft target. The returns are received on a 165-ft triangular antenna assembly. Each side of this tower consists of 111 individual antenna elements, each connected to an individual receiver. The composite result of signals received determines the al-

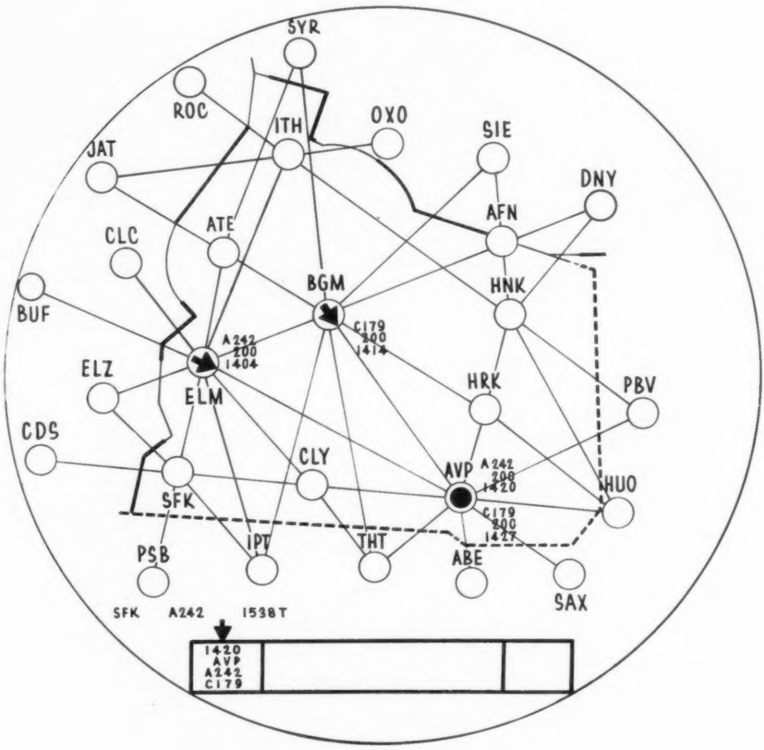

FIG. 7.—PICTORIAL CONFLICT DISPLAY, PLAN POSITION DISPLAY

titude of the target to within $\pm$ 250 ft within a radius of 50 miles and will resolve targets separated by as little as 1,000 ft.

The sixth function of the system is radar track-while-scan. This function is accomplished using radar video from 3-D radar, conventional radar or the air traffic control radar beacon system. Using a hybrid analog/digital video tracking sub-system, each target is tracked and displayed to the controller as radar video with an alpha-numeric tracking tag containing aircraft identity, speed, destination, and other pertinent information. This appears on a bright

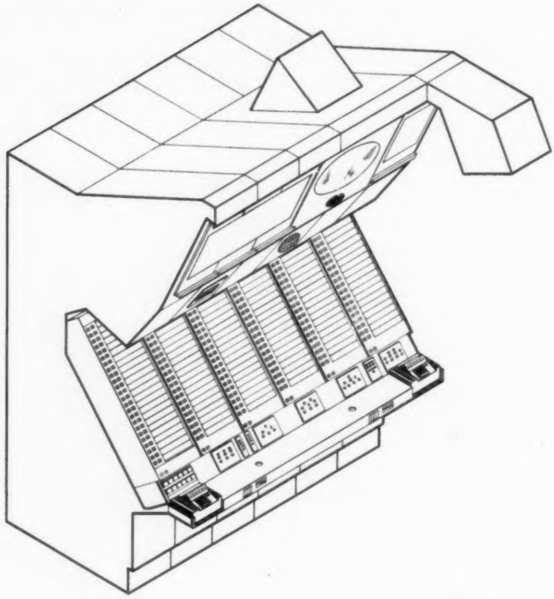

FIG. 8(a).—ATC/DPC TABULAR BAY, CONSOLE TYPE IVc

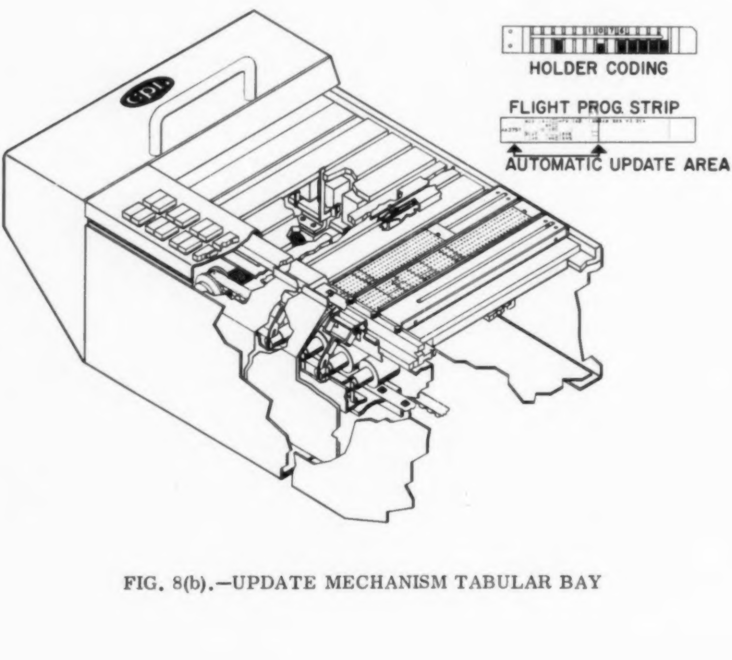

FIG. 8(b).—UPDATE MECHANISM TABULAR BAY

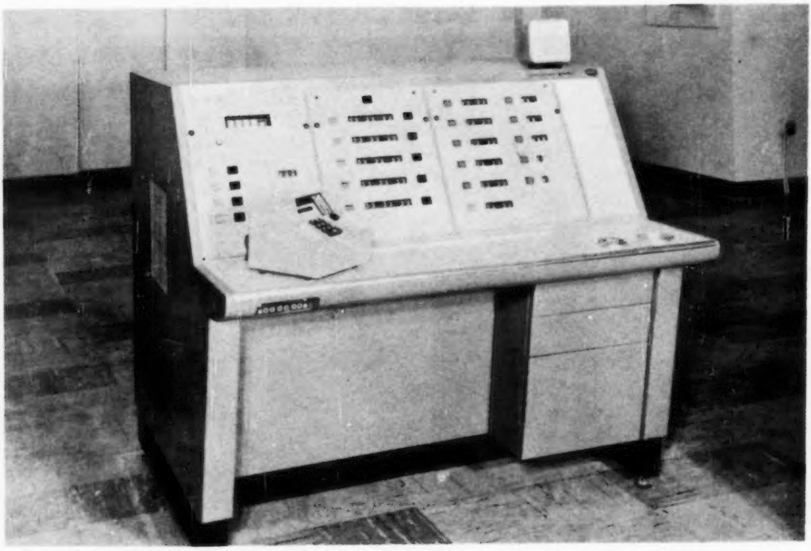

FIG. 9.—FLOW CONTROL CONSOLE

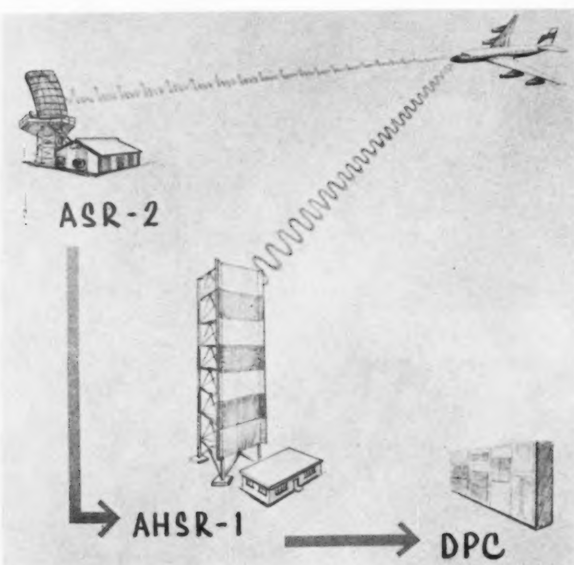

FIG. 10.—3 D RADAR

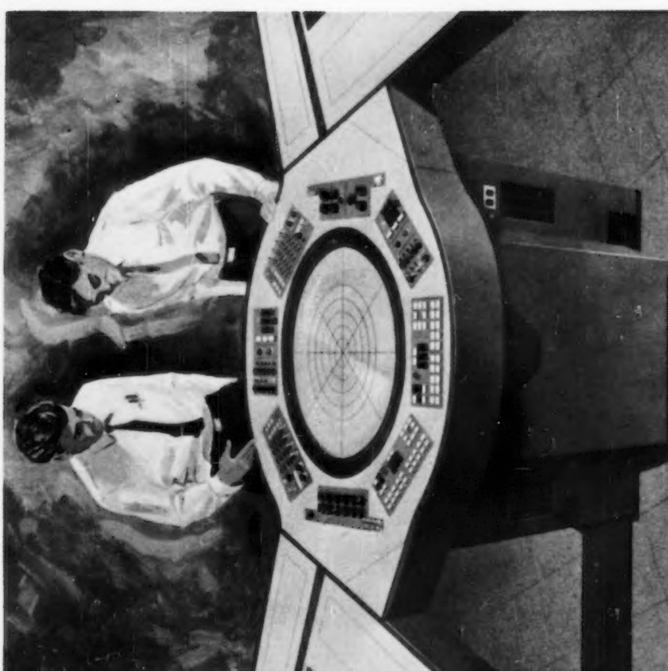

FIG. 11(a).—PLAN POSITION DATA DISPLAY

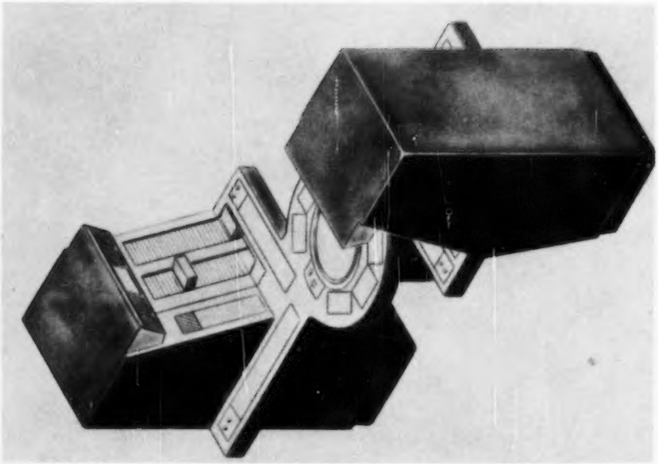

FIG. 11(b).—RADAR SECTOR CONSOLE

FIG. 12.—SEQUENCE CONSOLE

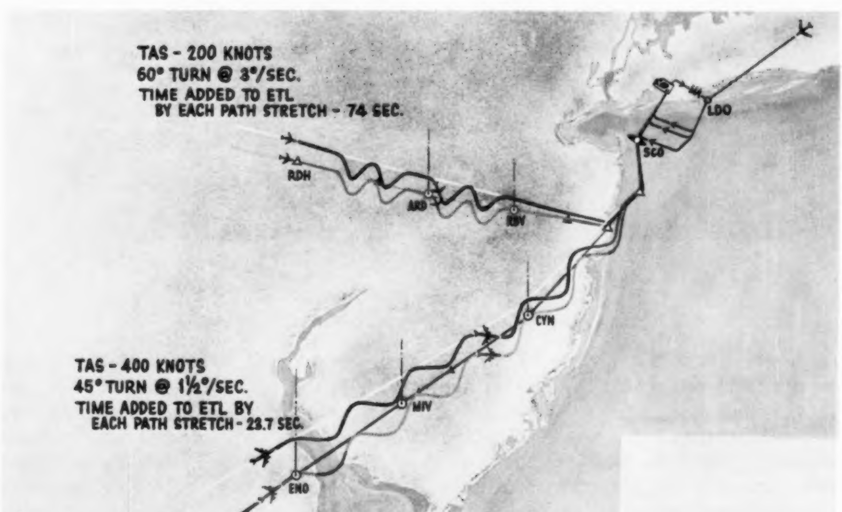

FIG. 13.—PATH STRETCHING AS AN AID TO SEQUENCING FOR DPC

radar display using the Hughes' Typatonatron Direct View Storage Tube illustrated in Fig. 11. Around the periphery of this display are located the beacon video processing equipment and video tracking sub-system controls. This bright display is normally located between two pylons of automatic up-dating tabular bays that are used in transfer-of-control and back-up procedures.

The seventh function, profiles and sequencing, is probably the most complex insofar as computer operations are concerned. Considerable test and experimentation remains to be done before this function is fully firmed up. Basically, it is a concept of arranging for the orderly arrival of traffic at the final approach gate. This is accomplished by using a stored descent profile for each aircraft type, computing a probable time of arrival and displaying this on the

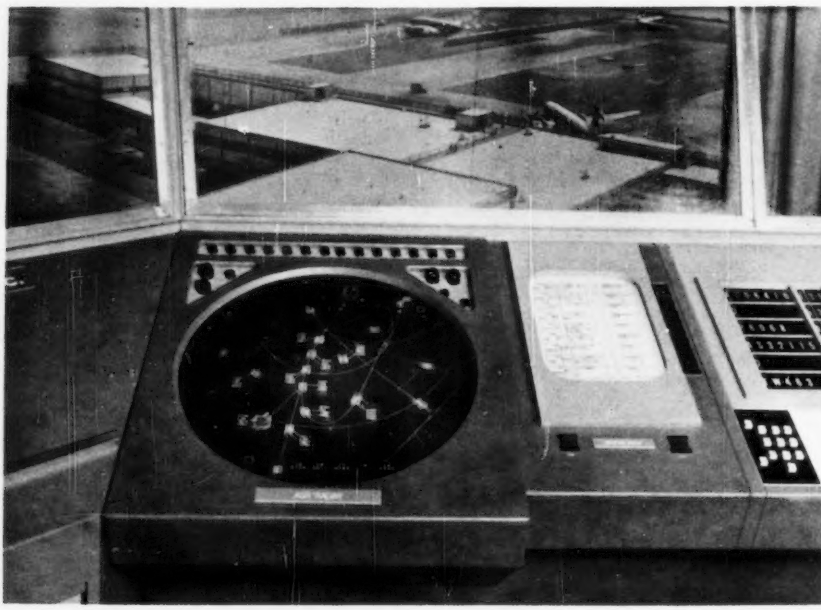

FIG. 14.—LOCAL CONTROL CONSOLE

Sequence Console shown in Fig. 12. Her columns of data indicate the available landing and departure times that are nominally set at 1-min intervals for 60 movements per hr but are adjustable over a substantial range. When the initial computations are made, the aircraft appears in one of the two awaiting assignment columns. The controller decides the landing sequence to be assigned and transfers the aircraft identity to the appropriate column for either main terminal or a satellite airport. The speed or other corrections necessary to make good the assigned landing time is determined and appears on the Sequence Console and the Radar Sector Console. Thereafter, computer computations based on aircraft actual performance are followed by the track-while-

FIG. 15(a).—TOWER CAB EQUIPMENT

FIG. 15(b).—SIMULATOR PILOTS AT WORK

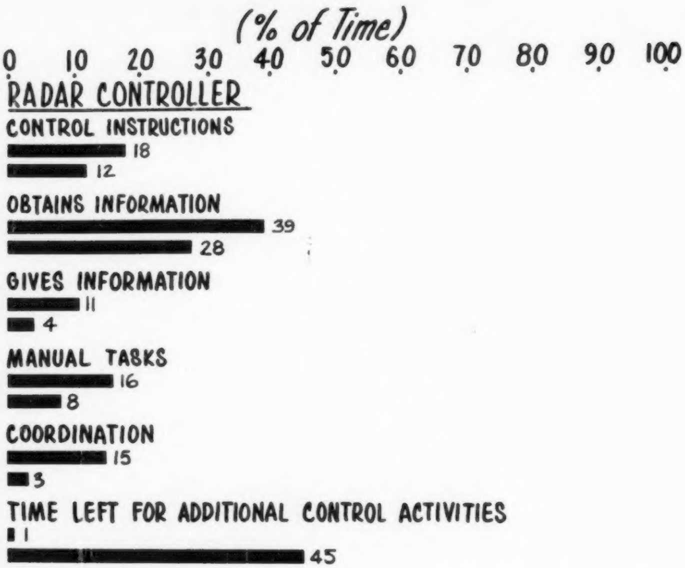

FIG. 16.—RADAR CONTROLLER ACTIVITIES, MANUAL VERSUS DPC

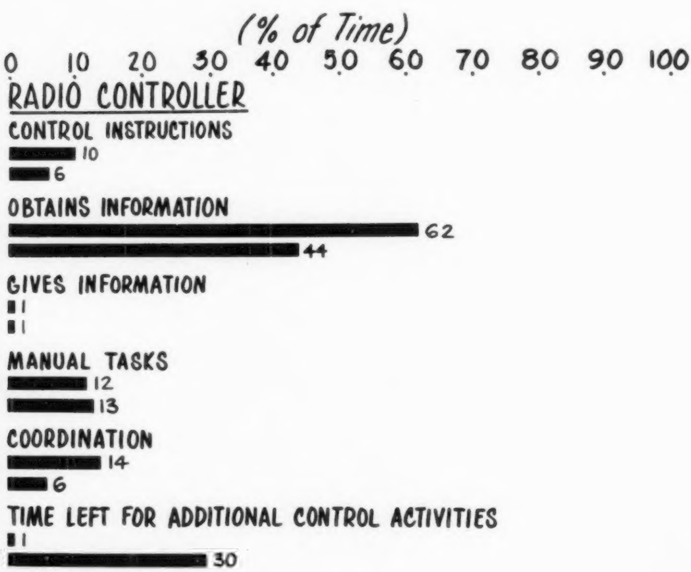

FIG. 17.—RADIO CONTROLLER ACTIVITIES, MANUAL VERSUS DPC

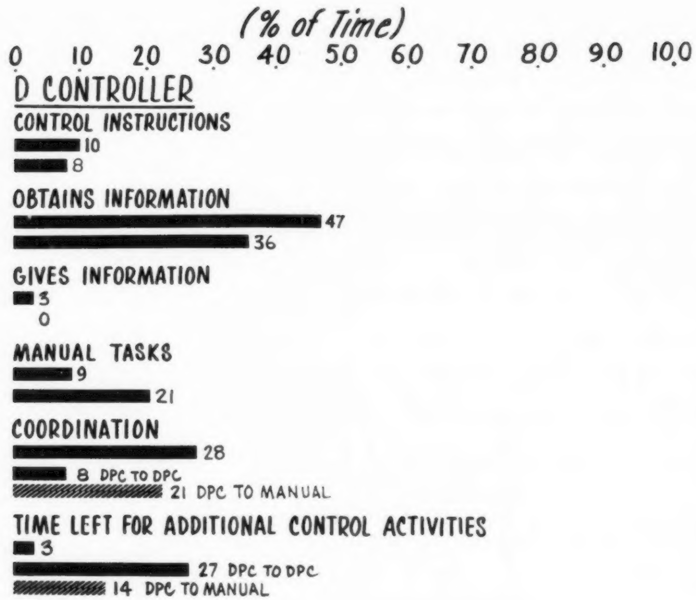

FIG. 18.—D CONTROLLER ACTIVITIES, MANUAL VERSUS DPC

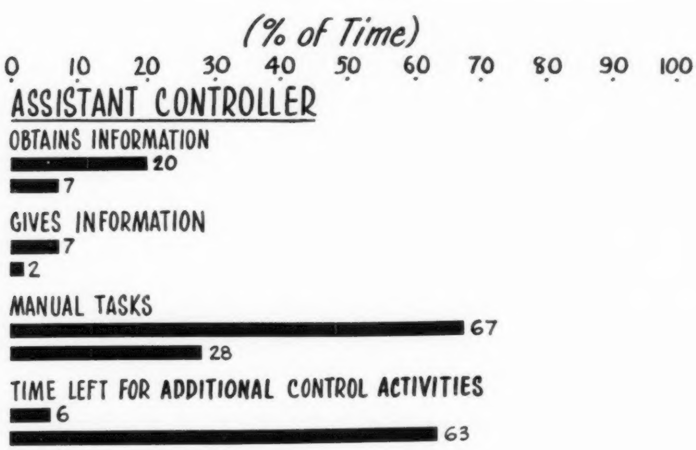

FIG. 19.—ASSISTANT CONTROLLER ACTIVITIES, MANUAL VERSUS DPC

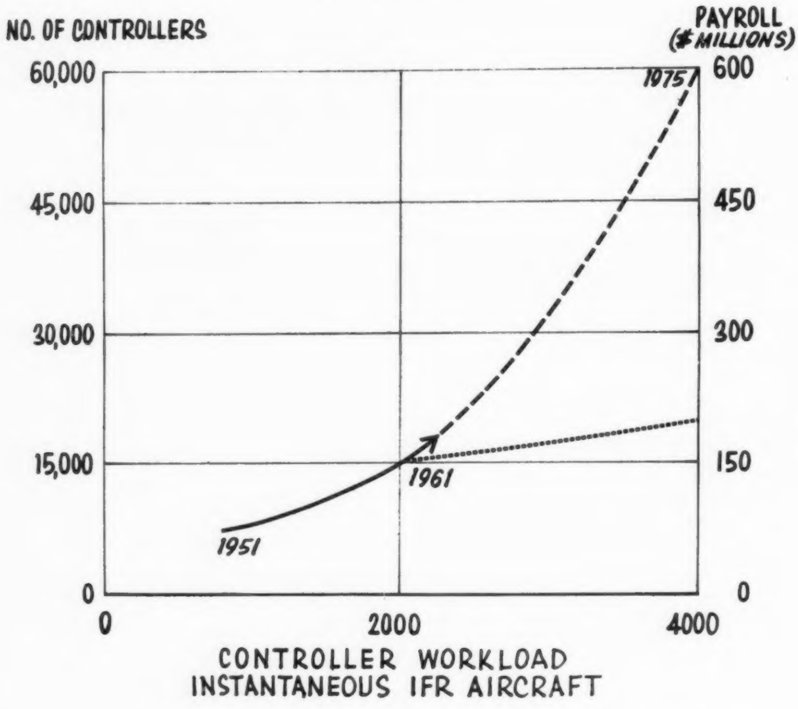

FIG. 20.—IMPACT OF AUTOMATION ON AIRCRAFT/CONTROLLER RATIO

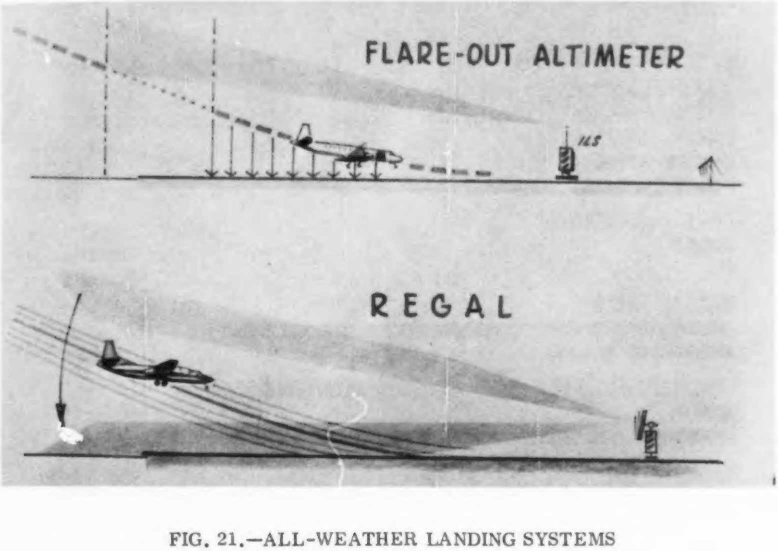

FIG. 21.—ALL-WEATHER LANDING SYSTEMS

scan system keep this information up-dated, and appropriate instructions are given to the pilot for compliance. Fig. 13 illustrates the path-stretching maneuvers that may be used in lieu of speed control but, as I have indicated, considerable test and experimentation remains to be done in this area. Function eight which is integration of the radar beacon system has previously been cited. This function is accomplished using the Beacon Video Processing Equipment. This equipment will provide for experimentation with altitude reporting on the beacon system to supplement the 3-D radar particularly at ranges beyond 50 miles. The accuracy of air derived beacon reported information will remain constant, whereas the accuracy of the ground based radar system decreases with increasing range. Using beacon, the controller will be able to rapidly accomplish the positive identification of aircraft, rapidly read out and confirm identity and altitude, and filter his display either by assigned beacon code or by selecting appropriate altitude layers.

The Plan Position Data Display with its identified track radar targets is remoted to the tower as a bright-bright TV display, viewable in full sunlight. Fig. 14 shows a mock-up of this display and the vidicon remoting of the departure strips. The full tower tab layout with bright-bright ASDE radar and the Flight Data Console is illustrated in Fig. 15. These tower CAB Displays together, with a Bright Precision Approach Radar display are among those that are candidates for early peel-off and application.

The entire DPC complex has been delivered to the FAA test facility at Atlantic City, N. J., where it will undergo test and experimentation including both technical and operational evaluations. One of the principal test tools is a large scale aircraft target simulator that simulates radar returns based on the flight paths followed by women operators serving as aircraft pilots. These girls become intensely involved in the program and just like regular pilots, complain if held or diverted too frequently. Figs. 16, 17, 18, and 19 illustrate the anticipated improvement to be achieved through the use of automation, whereas Fig. 20 illustrates the necessity for this increased efficiency in order that the number of control personnel may be held to reasonable limits while at the same time taking care of the explosive growth in air traffic requirements.

Two of the improved landing systems currently (1961) under development are illustrated in Fig. 21. First, is the flare-out altimeter system supplementing the present ILS and (lower Figure) the Regal scanning beam landing system.

CONCLUSIONS

The Bureau of Research and Development, beginning with its predecessor organization, the Airways Modernization Board, has for the past four years had underway a comprehensive program of inter-related projects that tackle the air traffic control problem on a total-system basis. No great detail has been presented herein, and some projects have not even been mentioned. For the most part they are all reaching the test and evaluation phase, and the next two years will find significant implementation decisions being made. Included in the projects that have been slighted are the AGACS, Air Ground Air Data Link; TRACE, the taxiway guidance system; and many others. Additionally, there are numerous in-service improvement or quick-fix projects such as the TV Marker Radar Hand-Off System to be used with existing scan converted

bright radar displays and the two-color high-speed printer modification to the UNIVAC on-line computer system.

DISCUSSION[a]

FROM THE FLOOR.—Is it anticipated that air traffic control innovations, which will permit the controller to spend less time bookkeeping and more time in actual controlling will, in turn, permit closer spacing of aircraft on final approach than the present 3-mile minimum spacing?

RESPONSE.—We think "yes," but this must still be proven through simulators that we now have. We must achieve less than 3-mile separation between aircraft on final approach in order to reach the goal of 60 movements per hr. Although whether or not we can reach 60 movements per hr is contentious, we think there is a possibility of getting there.

FROM THE FLOOR.—The basic assumption used by Stafford and Warshow[2] is that runway priority is given to landing aircraft; therefore, departing aircraft are delayed until there is a gap between landing aircraft. Will the sequencing procedure mentioned permit a dividing up of this delay between arriving and departing aircraft?

RESPONSE.—Yes, the actual controls under the Sequencing Council Group permit varying the ratio of arrivals and departures. The exact range may be something like three arrivals for every one departure. In actual practice, of course, this particular sequence wouldn't be practicable very long.

[a] The full discussion from the floor was tape recorded, but for the sake of clarity and brevity the remakrs were slightly condensed and, occasionally paraphrased. In some cases the identity of the discusser could not be determined.

[2] "Airport Design by Economic Analysis," by Paul H. Stafford and Martin A. Warskow.

Journal of the
AIR TRANSPORT DIVISION
Proceedings of the American Society of Civil Engineers

TRENDS IN AIRCRAFT DESIGN AFFECTING THE AIRPORT

By Ralph T. Glasson, Jr.,[1] and Weldon E. Rhoades[2]

SYNOPSIS

The airlines and aircraft manufacturers are continually striving to meet and solve airport and noise problems. The effect of some of the newer types of jet aircraft are presented to allow the study of their effect on the airport and the surrounding community.

INTRODUCTION

Following two years of jet transport operation, it is possible to examine some problems from a different viewpoint. At previous airport conferences, considerable attention was focused on problems of noise, runway length, and runway strength. This discussion reviews the progress made toward solution of these problems. An indication of aircraft and engine design developments affecting these problems is included. These comments are confined to subsonic transport aircraft.

NOISE

Noise has been the "stickiest" of the problems faced by the industry in introducing jet service. For the first time, man really has the ability to make

Note.—Discussion open until January 1, 1961. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Air Transport Division, Proceedings of the American Society of Civil Engineers, Vol. 87, No. AT 2, August, 1961.

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noise affecting communities throughout the world. Although the airlines have been deeply involved, the problems of airport noise are only partially under their control. Because of the tremendous implications of this problem, almost everyone has been involved, including aircraft manufacturers, engine manufacturers, airlines, airport operators, airport designers, local and Federal governmental agencies, the press, and innumerable consultants. Despite much confusion and conflicting information, considerable progress has been made.

There are basically two methods of reducing noise. The first is to suppress it at the source; the second is to increase the distance between the source and the receiver.

The initial attempts to suppress noise at its source involved multi-million dollar expenditures by manufacturers and airlines for the design and installation of devices externally mounted aft of the jet engine. Some of these early "monstrosities" were discussed by Donald Buck.[3] The most satisfactory compromises among these early devices are installed (as of 1961) on the operating fleets of jet airliners. An advanced knowledge of aerodynamics and thermodynamics is not required to see the inefficiencies involved in these devices. The annual cost in added drag and decreased thrust is measured in tens of millions of dollars. Nevertheless, the ingenuity and resourcefulness of the engineers who designed these suppressors should not be minimized. Regardless of cost, very little more could be done to suppress noise at its source by use of these devices alone.

The other method of reducing noise is to move the source and receiver further apart. Prescribed approach zones, clear zones, and local ordinances can help by discouraging noise-sensitive community activities from locating in immediate proximity to established traffic patterns. Usually, however, the aircraft flight path is altered to increase distance between the source and the receiver. Flight paths have been altered vertically by climbing and descending the jets as steeply as possible, consistent with safety. The industry has established preferential runways, departure patterns, and approach patterns to minimize the annoyance to airport neighbors.

Uniform procedures have been established governing climbout airspeed after take-off, altitude at which power reductions will be made, and turns away from sensitive areas. These procedures have been supplemented by special procedures and regulations catering to the problems peculiar to individual communities. There are obvious limitations to the relief attainable by flight path alterations.

The problem of air traffic control and flight safety cannot be subordinated to noise abatement. Airplanes must still land and take off, and someone is going to hear them. However, progress has been made through cooperation and the constructive efforts of all parties concerned. Legal actions and excessive regulation have not been found necessary.

RUNWAY LENGTH

Most airports now receiving jet service have provided runways of adequate length, at least for operations of a domestic airline. The coastal airports have

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[3] "Civil Jet Transport Noise," by Donald A. Buck, Proceedings, ASCE, Vol. 83, No. AT2, December, 1957.

had runway extension programs that make them quite adequate. Restrictions on payload due to inadequate runway length have not been too severe. There are still a few cases in which lack of a long secondary runway imposes substantial restrictions when adverse surface winds exist.

A previous paper[4] included runway-length recommendations for nine airports. As of 1961, eight of those nine airports have runways meeting, or exceeding, the requirements specified. The ninth has a runway under construction that will eliminate its deficiency.

It has been well known that high-altitude airports need longer runways. Unfortunately, the expansion programs at some of these airports have not been completed as soon as anticipated.

The jets introduced in 1959 requried relatively long runways. The SR-422 series performance regulations were more demanding than anticipated at the time the first group of jets was ordered. In addition, some manufacturers obtained disappointing performance on early versions of their jets. Engine and airframe manufacturers have met these problems successfully. Engine thrust levels were increased almost immediately by 5% to 10%. High lift devices such as slots, slats, and leading edge flaps were added at great expense. These devices will be discussed subsequently in greater detail. New models incorporating aerodynamic improvements and higher performance engines were offered for some initial deliveries and for retrofit on delivered aircraft. In almost all cases, it appears that the manufacturers have equalled or bettered the original contract specifications with respect to runway length requirements.

RUNWAY STRENGTH

Runway strength has been marginal. Difficulties have been most evident at those airports heavily used for jet training activity. Among the most difficult operational problems encountered during the past two years has been the closing of primary runways for repair and reconstruction. At one time last year, jet operations were conducted from Denver with only a single 7,000 ft runway in use.

RUNWAY WIDTH

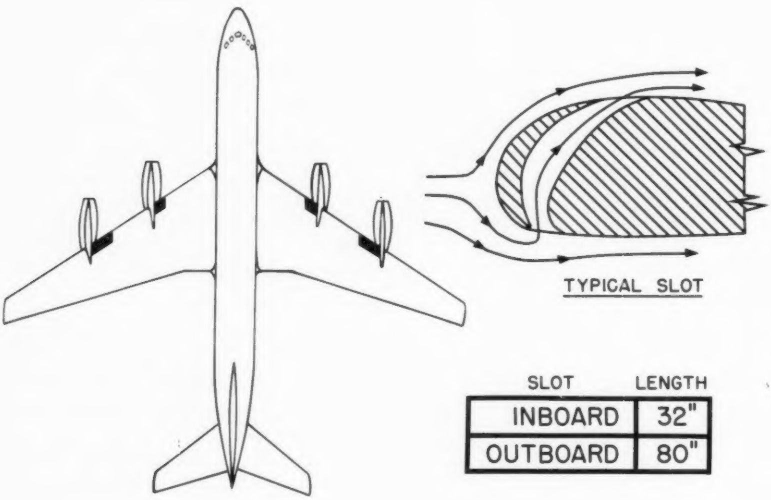
The 150-ft runway width has proved satisfactory for turbojet aircraft operations. Many aircraft now on order (such as the Caravelle, Boeing 727, and British aircraft) have engines mounted on the aft fuselage. Mounting engines close to the aircraft center line tends to minimize two problems related to runway width. Ingestion of foreign material is less likely, because engines are higher from the ground and do not overhand the runway edges. Also, the problems of assymmetrical thrust are minimized.

RUNWAY CLUTTER

Jet operations during winter months have been severely hampered by slush and snow on the runways. Due to the higher lift-off speeds of the jets, their

4 "A Statistical Approach to Runway Length," by Ralph T. Glasson, Proceedings, ASCE, Vol. 83, No. AT2, December, 1957.

acceleration is more seriously affected than piston or turboprop aircraft. At present, United Air Lines does not operate jet aircraft when slush, standing water, or wet snow exceeds a depth of ½ in. Operation in ½ in. of slush requires off-loading of a DC-8 by 16,000 lb to maintain the same take-off performance as on a dry runway. Performance regulations on slush accountability have been proposed by the FAA. These proposals will require very accurate measurement of precipitation depths. It is difficult to visualize the measurement of depths by calipers when the non-uniformities of precipitation and roughness of runway surfaces are considered. The solution of problems of measuring and reporting of depths and densities, and of clearing slush from



SLOT	LENGTH
INBOARD	32"
OUTBOARD	80"

FIG. 1.—DC-8 SLOTS

runways, requires the constructive cooperation of airport operators, government agencies, and the air carriers.

HIGH LIFT DEVICES

All manufacturers in the United States are now incorporating high-lift devices on the wing leading edge of their jet transports.

Douglas Aircraft Company has incorporated wing slots in all DC-8's. These wing slots reduce required take-off field length at a given weight by as much as 9%. From a given length runway, 10,000 lb more payload can be accommodated on the slot equipped aircraft (Fig. 1).

Boeing Aircraft Company incorporated a Kruger Leading Edge Flap on the B-720 and on some models of the B-707. On later versions of the B-707 and on some future models such as the B-727, they are using sophisticated combinations of wing slots and Kruger flaps (Fig. 2).

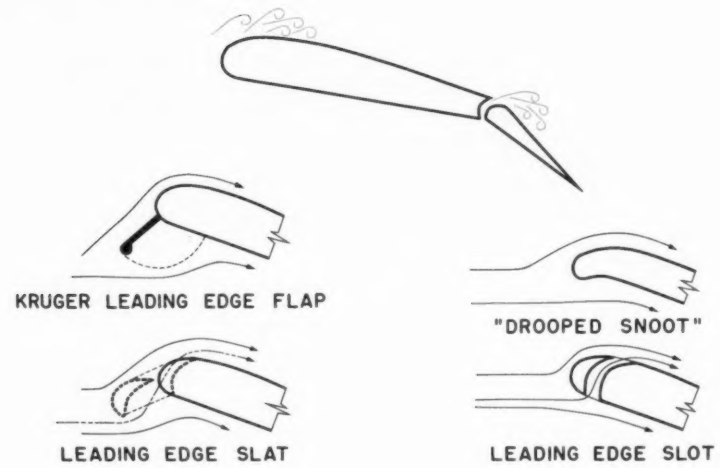


FIG. 2.—LEADING EDGE HIGH LIFT DEVICES

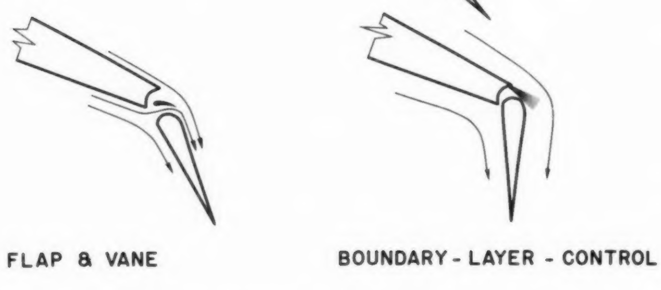


FIG. 3.—TRAILING EDGE HIGH LIFT DEVICES

Convair utilizes wing slots on some models of the CV-880 and on the CV-990.

All of these devices are designed to (1) provide additional margin for error during take-off, (2) permit lower take-off speeds, (3) shorten runway length requirements, (4) permit fuller exploitation of the maximum lift capabilities of the trailing edge flaps.

In addition to these wing leading edge devices, the manufacturers are working on other developments to increase maximum lift coefficients, thereby lowering take-off speeds and shortening runway requirements. Primary emphasis appears to be concentrated on the development of mechanically and aerodynamically sophisticated flaps (Fig. 3).

Use of boundary layer control, particularly blowing air over the flaps to increase maximum lift, is receiving considerable attention. This, of course, has been proposed for years, but some manufacturers now plan to certificate transport aircraft using this device.

ENGINE DEVELOPMENT

Engine manufacturers, in the United States and in the United Kingdom, have kept pace with ever-increasing demands for higher performance aircraft. The most direct way to shorten take-off runway requirements is to increase take-off thrust. Higher thrust also increases the altitude attainable prior to passing over-populated communities.

Thrust increases have followed two channels. One method has been to raise the thrust level of the straight turbojet engine. The second has been the development of the turbofan engine (the term turbofan is used herein to identify the entire group of bypass, turbofan, and aft-fan engines).

The reliability of aircraft gas turbine engines has been excellent. This reliability, plus extensive detailed development of components and materials, has permitted the manufacturers to increase thrust levels quite rapidly. In 1955, when the first DC-8 and B-707 contracts were signed, the JT3 engine was quoted at 12,500 lb thrust (S. L. Static). This engine is now rated at 13,500 lb thrust. When the JT4 engine was first offered commercially, it was quoted at 14,000 lb thrust. The JT4 is now rated at from 15,800 lb to 17,500 lb, depending on jet model used by the various carriers.

TURBOFAN ENGINES

Turbofan engines are now (1961) being specified in virtually all contracts for current and future transports. Basically, a turbofan is a turbojet with fan stages added to accelerate more air. A portion of the energy normally used to develop jet thrust is extracted to turn the fan. In a turbofan engine, the velocity of the jet is lowered, and the propulsive efficiency is increased. This increased propulsive efficiency can be used to obtain greater thrust, or lower fuel consumption (Fig. 4).

The thrust of a turbofan engine decreases more rapidly with speed and altitude than a turbojet engine. Therefore, the size of the turbofan engine is usually dictated by the cruising thrust required. When the inevitable design compromises are made, a turbofan powered aircraft ends up with more than sufficient take-off thrust.

The combination of higher take-off thrust and decreased fuel requirements reduces runway length requirements drastically. Because the size of the cabin and structural limitations do not permit additional payload, the lower fuel comsumption results in lower take-off gross weight. Lower take-off gross

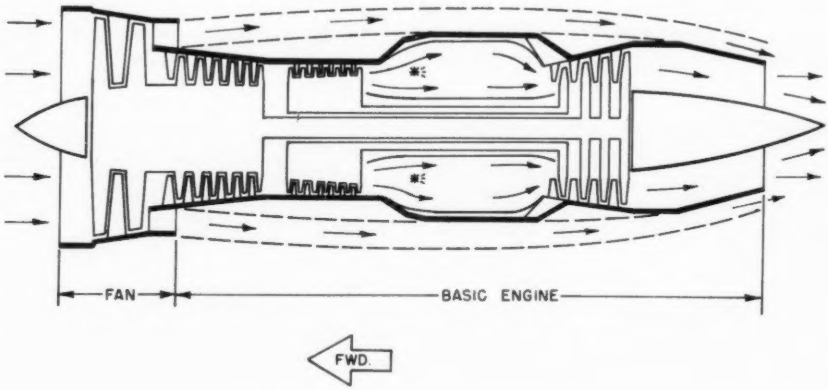


FIG. 4.—TURBOFAN ENGINE

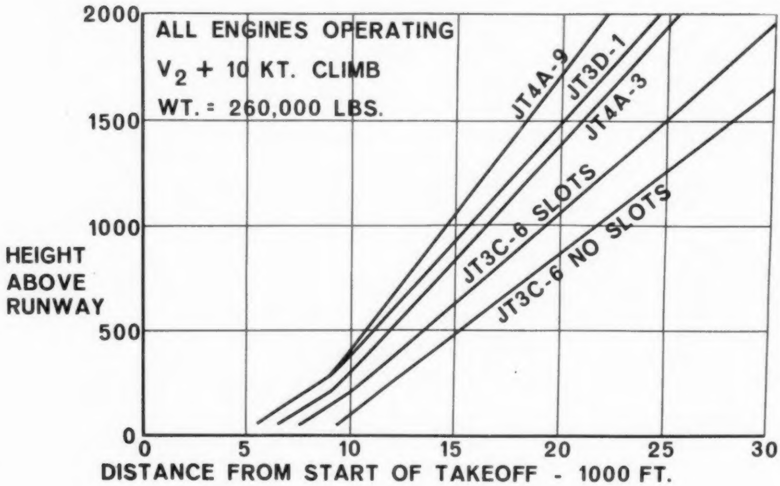


FIG. 5.—DC-8 FLIGHT PATHS

weight reduces the required runway length. The added take-off thrust available from turbofan engines itself reduces the length of runway required still further.

The combination of aerodynamic improvements and engine development indicates that runways adequate for today's jets will be adequate for subsonic

transports of the future. Requirements at specific airports must still be determined by proper consideration of airport elevation, climatological factors, and distance to be flown. These requirements should be discussed with the individual air carriers operating from the airport.

The foregoing improvements in aerodynamic design and engine development will result not only in shorter runway lengths, but in steeper climbout flight paths. This increase in flight-path angle will put considerably more distance between the aircraft noise generators and the communities adjacent to the air-

FIG. 6.—CARAVELLE VI R

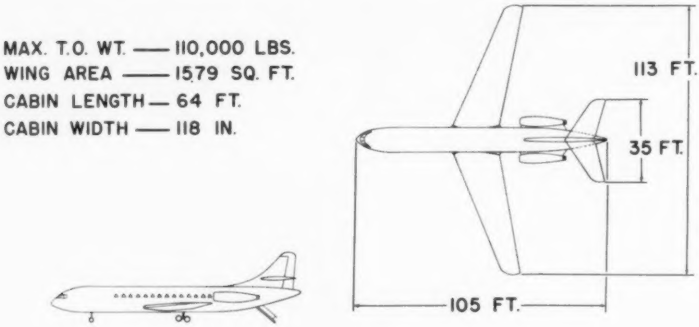


FIG. 7.—GENERAL CHARACTERISTICS OF CARAVELLE

port. For example, the DC-8 powered by JT4A-9 engines can attain twice the altitude over a point 4 miles from the start of take off, than could the original JT3C-6 powered DC-8. This increased altitude drastically reduces the perceived noise level, because thrust can be reduced to equivalent levels on either version (Fig. 5).

SHORT-MEDIUM RANGE AIRCRAFT

United Air Lines has ordered two types of aircraft for the short-medium range travel market. These two aircraft will be discussed briefly as typical

of the next generation of jets to make an appearance in the domestic United States.

THE CARAVELLE VI R

The Caravelle VI R (Fig. 6) is an advanced version of the popular French turbojet that has been operating successfully in Europe for several years. It

FIG. 8.—NOISE SURPRESSORS ON CARAVELLE

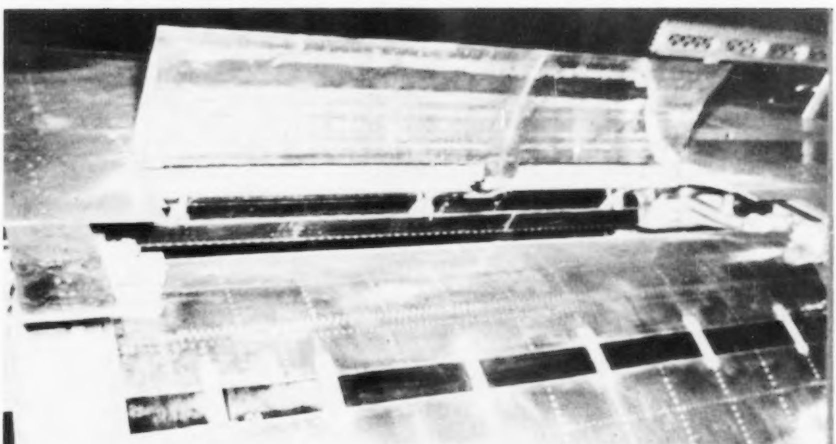


FIG. 9.—SPOILERS ON CARAVELLE

is powered by two 12,080 lb thrust Rolls-Royce engines mounted aft on the fuselage. Cruising speed is more than 500 mph, and the range is nominally 1,000 miles. Maximum take-off weight is just 110,000 lb, slightly over that of the DC-6B (Fig. 7).

FAA Performance Regulations require that minimum climb gradients be met with an assumed engine failure at the most critical point during the take off. The Caravelle meets these requirements with one engine operating, or with an

assumed 50% loss in thrust. It is obvious that when both engines are operating on a normal take off, its full thrust will permit high rate ascents. By attaining altitude prior to passing over communities, it will help solve some of our noise problems. In addition, this new version of the Caravelle will be equipped with noise suppressors (Fig. 8).

The relatively low take-off weights and the bogey gear will minimize runway strength requirements. The UAL version will also have ground spoilers to shorten landing roll (Fig. 9).

Runways of 6,000 ft to 6,500 ft will be adequate for airports from which maximum trip lengths of 300 to 500 miles are to be flown. When the maximum range of 1,000 miles is to be exploited, runways of 7,000 ft to 9,000 ft will be required. Operation from high-elevation airports, such as Denver, will require runway lengths similar to those of the DC-8 and B-720. Again, it is em-

FIG. 10.—BOEING 727

phasized that requirements at individual airports should be discussed directly with the airline operators involved.

BOEING 727

The 727 (Fig. 10) is the most recent addition to the family of transports offered by Boeing Aircraft Company. It is scheduled to begin test flights in 1962, with deliveries starting in late 1963. It will be in airline service in 1964.

The 727 (Figs. 11 and 12) is powered by three aft mounted Pratt and Whitney JT8D-1 turbofan engines of 14,000 lb thrust each. The three-engine design results from compromises to obtain better performance than possible with a twin engine aircraft and lower short range operating costs than with a four engine aircraft.

Cruising speed will be about the same as the present jets. Maximum practical operating range will be 1,500 miles to 1,700 miles. Maximum take-off weight will be about 142,000 lb about the same as a DC-7C.

This aircraft will incroporate recent developments in advanced design triple-slotted trailing edge flaps (Figs. 13, 14, and 15). Its combination of leading edge flaps and slats will further increase its maximum lift coefficient

FIG. 11.—GENERAL CHARACTERISTICS OF BOEING 727

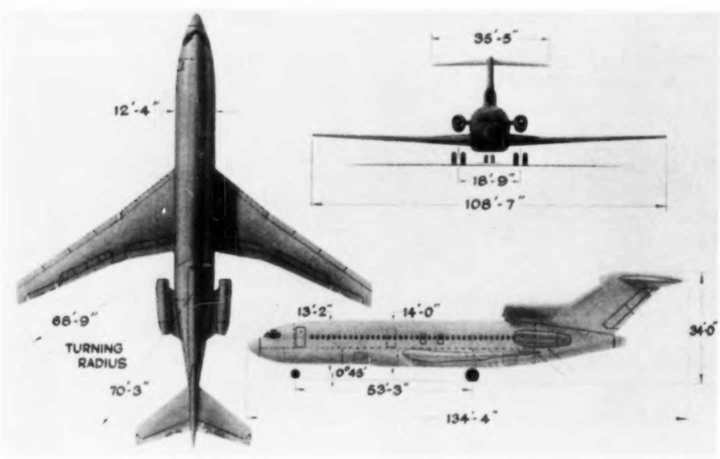


FIG. 12.—GENERAL ARRANGEMENT OF BOEING 727

which will be about 25% higher than on the B-720. The ratio of engine thrust to weight at take off with all engines operating will be 25% higher than the Boeing 720.

This combination of high lift coefficients and high thrust/weight ratio means excellent airfield performance.

Minimum certificated landing distance for dry runways at sea level is expected to be below 5,000 ft. Runways 6,000 ft to 7,000 ft long should be adequate for relatively short range services except for high-elevation airports. Runway lengths adequate for Caravelle operation will accommodate the B-727.

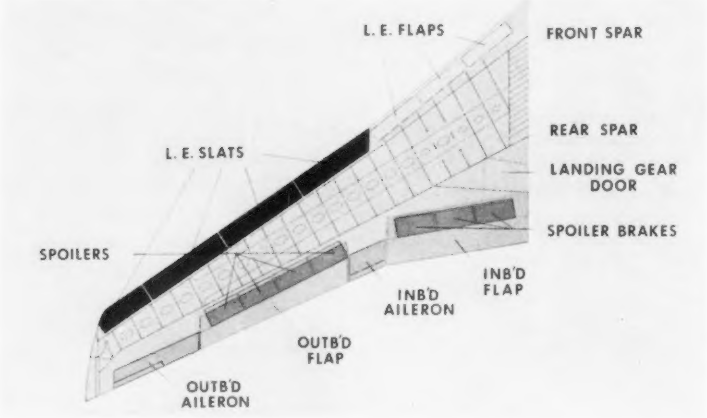


FIG. 13.—WING PLAN OF BOEING 727

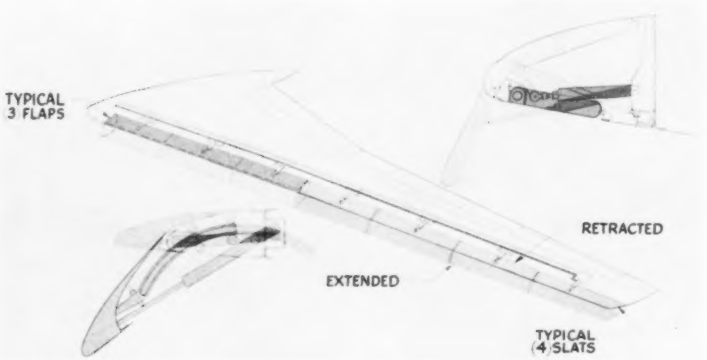


FIG. 14.—LEADING EDGE FLAP AND SLOT SYSTEM FOR BOEING 727

Two developments that are under investigation for possible incorporation on the Boeing 727 may be of interest. First, structural provisions have been made for the installation of arresting gear. The decision to actually incorporate such a device has not been made. Another interesting development is the brake system. Development and testing of a liquid cooled brake will be carried out concurrently with the conventional heat sink brake. A prototype liquid

cooled system will be installed and service-tested on a United Air Lines Boeing 720. Successful development of this system would mean lower temperatures on the breaking surfaces and, therefore, increased reliability. Improved braking is important to an aircraft flying short route segments with multiple landings and take-offs.

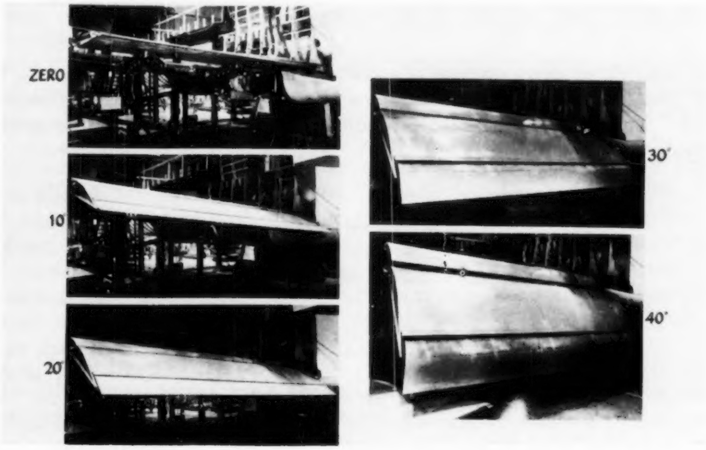


FIG. 15.—HIGH LIFT (TRAILING EDGE) FLAP FOR BOEING 727

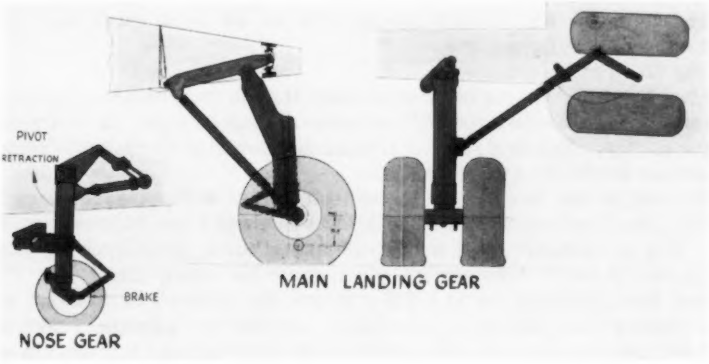


FIG. 16.—LANDING GEAR FOR BOEING 727

Recent tests of the Boeing 727 engine reversing system indicate that 50% greater reverse thrust will be attainable from the three engines on the 727 than is possible using all four engines on the B-720. Although reversing is not used to demonstrate certificable field lengths, this will result in added safety margin for wet or slush covered runways.

The B-727 will incorporate a simple two-wheel gear (Fig. 16), rather than the bogey gear used on other jets. This will increase its runway strength requirements to about the level of the DC-7 and DC-7C.

High performance capability plus engines designed initially with nose suppression characteristics built in, will enable this aircraft to meet noise abatement objectives.

CONCLUSIONS

In the continuing development of existing aircraft and the design of future aircraft, the airlines and manufacturers are not overlooking airport and noise problems. This paper has indicated some of the areas in which progress has been made.

DISCUSSION[a]

FROM THE FLOOR.—Numerous questions were asked concerning characteristics of the Caravelle, which United Air Lines will introduce into the short medium range turbojet field, and of the Boeing 727, a future short/medium range turbojet transport. A summary follows:

Caravelle.

1. The United Air Lines version of the Caravelle will not utilize the emergency brake parachute with which the European version is equipped; the G. E. engines will have reversers in lieu thereof.

2. The approach and landing speeds will not be much lower than those of present subsonic jet transports.

Boeing 727.

1. Structural provisions have been made for the installation of a tail-hook, for possible use in conjunction with a cross-runway pendant, as an emergency arresting device. However, no such rapid deceleration as that experienced in Navy carrier landings is visualized.

2. No thought has been given to take-off assist devices such as catapults or JATO. (This was substantiated by an Eastern Air Lines representative who stated: 1) if an aircraft needs a take-off assist for a given runway, the indication is that it didn't have enough power from the start, and 2) the Eastern Air Lines specifications for the 727 require the aircraft to take off from a 5,000 ft runway, on a hot day, at maximum payload for a range of 600 miles).

3. The clearance between the bottom of the trailing edge flap and the ground will be approximately 2 ½ ft, with flat tires on the same side.

4. The Pratt and Whitney JT-8D turbofan engines will have internal noise suppression of both intake and exhaust.

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[a] The full discussion from the floor was tape recorded, but for the sake of clarity and brevity the remarks were slightly condensed and occasionally, paraphrased. In some cases the identity of the discusser could not be determined.

5. The approach and landing speeds will be markedly lower than existing turbojet transports. A Boeing 707 prototype, fitted with the flaps that will go onto the 727, has been flown at 75 knots.

6. With reference to the compatiability of the 727's rear-mounted engines with 8 ft blast fences, and Eastern Air Lines representative stated that blast fences would not be required. He quoted a temperature/velocity study as indicating temperatures 100 ft from the engines to be comparable to existing turbojet engine temperatures, and velocities of the 125 fps, 200 ft from the tail of the aircraft.

FROM THE FLOOR.—With reference to the authors' statement that current turbojet operations in cross-wind conditions were being inhibited to some extent by the short length of secondary runways, is there a real necessity for a secondary runway for cross-wind operations?

RESPONSE.—The requirement varies with the characteristics of prevailing wind conditions at individual airports. At Los Angeles, for instance, the several runways in the direction of the prevailing wind are quite adequate. At San Francisco, however, although the prevailing wind would permit westerly takeoffs most of the time, noise abatement measures and windshifts make it quite important to have an adequate secondary runway. Normally a secondary runway about 80% to 85% as long as the primary runway is adequate, but, again, this can vary at individual airports.

FROM THE FLOOR.—A representative of a medium hub airport described difficulties in selling local residents on the need for a runway extension to about 7,000 ft, as verified by the FAA and consultants, when a two-page advertisement in leading magaiznes stated unqualifiedly that the 727 can operate from a 5,000 ft runway.

NOTE.—Current FAA planning data for airports served by short/medium range turbojet aircraft is based on the known characteristics of the 720, rather than the probably shorter runway requirements of the still-on-the-drawing-board 727.

Journal of the
AIR TRANSPORT DIVISION
Proceedings of the American Society of Civil Engineers

SUMMARY OF SYMPOSIUM ON SUPERSONIC AIR TRANSPORT

By Reginald J. Sutherland,[1] M. ASCE

SYNOPSIS

The aircraft manufacturers have studied, at great length, the problems that will develop with the introduction of supersonic passenger planes. The design and operation of these planes and the method of handling them at airports are described.

The Symposium on Supersonic Air Transport that comprised the Fourteenth IATA Technical Conference was held in Montreal, Canada, on April 17 through 22, 1961.

The Conference was exceptionally well planned and conducted. It involved the advance preparation, by the IATA Secretariat and Technical Committees, of some 500 questions covering all phases of supersonic transport economic planning, design, construction, and flight and ground operations. The questions were submitted in advance to the IATA membership and industry representatives. They were intended to suggest subjects for technical papers as well as areas for investigation and study in preparation for the conference. In all, some fifty-three technical papers were submitted and also distributed in advance of the conference.

Approximately 650 delegates convened at Montreal representing some 130 organizations. The first two days of the Conference involved plenary sessions attended by all delegates at which questions pertaining to potential limitations,

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Note.—Discussion open until January 1, 1962. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Air Transport Division, Proceedings of the American Society of Civil Engineers, Vol. 87, No. AT 2, August, 1961.

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basic characteristics of the aircraft and aircraft design were discussed in general. The next two days were devoted to detail discussions of the questions pertaining to design, operations, and ground handling. These sessions were held simultaneously and were attended by the delegates most interested in these areas. On the last two days all delegates again attended plenary sessions at which the findings and implications of the detailed sessions were discussed and brought into focus.

BASIC CHARACTERISTICS

Before getting into a detailed study of the aircraft design it was considered advisable to set forth some of the basic factors that have a bearing on its operation. The items discussed in this area were as follows:

Traffic Potential.—Air traffic on a world-wide basis has shown a steady increase in volume over the past ten years. Most optimistic estimates of annual growth rates were in the range of 10% which would result in a demand for 150 + billion seat - miles by the 1970's. This would indicate a requirement for some 200 aircraft to 400 aircraft, depending on flight frequencies.

Flight Frequencies.—There was some indication that flight frequencies would increase based on experience with current operations that have resulted in a demand for higher frequencies as flight time decreased. Higher frequencies would result in better utilization which will be required to amortize the aircraft within a reasonable time.

Routes.—North Atlantic routes appeared to offer the best traffic potential. United States and Canadian transcontinental routes were also considered promising, as were Pacific routes.

Range.—Most delegates seemed to prefer a design range requirement on the order of 3,500 miles, recognizing that this would not be sufficient for some of the longer routes now being flown, but would result in reasonably efficient designs. There was, however, some discussion indicating that supersonic transports would eventually be operated on route segments as short as 1,000 miles.

Capacity.—Capacities would be governed by route traffic, flight frequencies, and weight limitations. The concensus ranged from 75 seats to 175 seats with dual class configuration flexibility a requirement. Weights would generally range from 200,000 lb to 450,000 lb.

Speeds.—Desirable speeds varied from Mach 2 to Mach 3. Some delegates were of the opinion that very little is known concerning the problems of supersonic flight and it would be better to proceed cautiously to Mach 2. Others felt that current studies and further research will provide enough answers to jump to Mach 3. The problem of ground travel time would become increasingly significant as these speeds are achieved.

AIRCRAFT DESIGN

Configuration.—Early discussion indicated that the most likely configuration, based on the current state of the art, would be of the carnard-delta form. However, there were enough questions raised to indicate that further study of the problems of adequate control, approach speeds, and landing attitude indicated that the designers would have to give this further investigation.

Fuselage Width.—There was considerable discussion of seating arrangements varying from 4 abreast to 6 abreast. Preference followed current practice of 4 abreast for first class and 5 to 6 for tourist. The indicated fuselage widths varied from 130 in. to 143 in. Finess ratio restrictions will have a definite bearing on the width. Cabin windows were considered necessary.

Length.—Most manufacturers indicated that fuselage lengths would be in the 160 ft to 200 ft range.

Span.—Probable span widths on the order of 0.6 of the length or 90 ft to 120 ft were indicated.

Wings.—Delta plan form with a straight trailing edge and a leading edge sweep seemed to offer the best possibilities.

There was some discussion of the advantages of variable sweep wings that would result in lower control, approach, and landing speeds. However, other factors such as the use of the wing for fuel storage, qreater structural weight, and the complexity and reliability of the variable mechanism along with increased cost may rule them out.

Boundary - Layer Control.—The possibility of using boundary layer control to improve performance particularly at low speeds was discussed and indications were that some form of it would be desirable. VTOL and STOL capabilities also would be desirable but highly improbable.

Fin Height.—There was some discussion of the necessity of keeping fin heights to current levels to avoid hangar obsolesence. The manufacturers indicated that this could be a problem unless they used folding wing tips similar to the B-70.

Power Plants.—The preference seemed to favor the turbofan engines with duct burning. One foreign manufacturer discussed the use of a ramjet type. The general opinion seemed to be that present conventional straight jet engines developed to higher thrust ratings would produce entirely too much noise to make them feasible for civil operations.

Power Plant Location.—Most designs indicated that grouping buried engines at the rear and under the fuselage was preferable. There was, however, some discussion of the use of podded engines but also some doubts regarding maintenance of satisfactory directional control in high-speed flight with engine failure. In any event thrust reversing would be used on landings and possibly in flight below Mach 1 for decelleration.

Fuels.—Currently used kerosene and JP-4, with the use of additives to improve their thermal stability characteristics, should be suitable for Mach 2 operations. For Mach 3, fuels of lower volatility and better thermal stability than can be obtained from existing kerosene type fuels will be required.

Landing Gear Configuration.—On this point the concensus seemed to indicate that a nose gear and a dual tandem main gear system similar to that used on current subsonic jets will be used.

Flight Characteristics.—The studies of the various manufacturers indicated that take-off, climb and descent, and landing speed characteristics would be generally similar to our current jets with some slight variations.

POTENTIAL LIMITATIONS

Aerodynamic heating will limit the selection of materials for supersonic transport in order to assure a reasonable total life of the airframe structure.

It was agreed that a guaranteed minimum of 30,000 hr would be required and desirable life would be 50,000 hr. The fact that supersonic transport would operate above Mach 1 on a average of only 60% to 65% the operating life of its useful life should be recognized.

It appeared that aluminum structures would be limited to temperatures in the area of 250° F which would represent a Mach Numbers of 2 to 2.4, and that steel or titanium could safely withstand temperatures up to 700°F for Mach Numbers on the order of 3 to 3.5.

It was also pointed out that the limiting effect of non-matallic materials used in certain parts of the structure such as windshields, windows, and seals would have to be taken into account. Sealing materials for fuel tanks, fluid lines, and cable insulation were also items for further study.

Finally it was brought out that the behavior of all materials used at the lower temperatures encountered at altitude when operating below Mach 1 would also have to be reckoned with.

Properties of the atmosphere will affect engine operation and possibly the safety and physical well being of the crew and passengers. Such properties will vary with altitudes. It was agreed that for Mach 2 cruising altitudes would be 50,000 ft to 70,000 ft and 60,000 ft to 80,000 ft for Mach 3. Ambient temperatures would be as low as -85° F.

Other discussions indicated that the ratio of oxygen to nitrogen would not change appreciably below 100,000 ft. Very little information was available on ozone content, but generally it was felt that it would vary from 0.1 ppm at 30,000 ft to 0.6 ppm at 100,000 ft, and that these values would change with seasons and latitudes. Such levels could result in intolerable concentrations as high as 10 ppm at cabin pressures. One solution might be to recirculate the cabin air. Relative humidity could very from 2% to 100%. It was generally believed that no particular difficulties due to radioactive particles were anticipated although nuclear testing could affect concentrations considerably.

Human limitations will govern certain aspects of operation. For instance acceptable floor angles could not be significantly different from current subsonic practice. Angles of bank did not appear to be a particular problem as in most cases passengers would not be able to judge the angle of bank from any visual reference. Gradual exposure to g forces without sudden change should be acceptable. Rate of change of cabin pressure should be held to the order of 300 fpm for descent and 600 fpm for climb. Noise levels inside the cabin should not exceed 75 db overall. Maximum cabin altitude should be kept below 6,000 ft.

AIRPORT OPERATIONAL PROBLEMS

Airport Pavement Strengths.—Gross aircraft weights as previously mentioned will probably range from 200,000 lb for Mach 2 designs and up to 450,000 lb for Mach 3. Regardless of whether or not the design follows current conventional practice or does go to the carnard-delta arrangement the landing gear will probably be of the familiar nose gear and two main gear type. The only unknown is the number of wheels and their layout. The probability seems to be that the nose will retain the usual dual wheels, but there is some possibility that the main gear might go to six wheels per leg for the higher gross weights. Wheel loadings will depend on the final geometry of the gear. Equivalent single

wheel loadings as high as 120,000 lb are possible. Such a wheel loading would mean strengthening or completely rebuilding pavements depending on local conditions. Fortunately, not too many airports will be affected as supersonic transport service will probably be limited to a dozen or so in the United States and to one or two airports in most foreign countries.

Runway Pavement Smoothness.—Depressions and high spots have been a problem with current jet operations, particularly if they are located at critical points such as the area where rotation speeds are usually reached. Such conditions will continue to be a problem with supersonic aircraft and could become much more critical. Regularly spaced uneven joints of concrete pavement and flush runway lights might possibly induce sympathetic dynamic vibration response that could be serious.

Snow and Slush Problems.—Slush will undoubtedly become much more of a problem than it has been with current operations due to higher take-off speeds, and there does not appear to be a ready solution to it. Clearing with vehicular equipment ties up the runway too long and radiant heating is not practical. One possible way of partially solving the problem is to use narrower tires; however, this would result in reducing the tire contact areas, thereby increasing unit pavement loading.

Runway Lengths.—Manufacturers seemed to feel fairly confident that runway-length requirements for take-off will not exceed those now in use for subsonic jets. However, airlines pointed out that certificated lengths usually turned out to be greater than manufacturers estimates and even these were usually not adequate for everyday operations under varying weather conditions. One factor that will tend to keep take-off length requirements down is the excess power required for transonic operation that should be available for take-off performance improvement.

Another thought was that the accelerate-stop distance requirement may very well turn out to be the controlling factor for runway-length requirements. Landing-length requirements were generally expected to be in the neighborhood of 7,000 ft. Thrust reversing will be used. There was also some discussion of the possible use of chutes, but the concensus seemed to be against them mainly because they are most effective at high speeds and do present quite a maintenance problem. The regular use of arresting devices was considered to be very improbable.

Runway Widths.—With the carnard-delta or more conventional configurations wing spans will undoubtedly be less than those of current jets; therefore, there is no reason why 150 ft runway widths should not be adequate. Crosswind characteristics will depend on lateral stability and this should be at least as good as with current jets, if boundary layer control or other auxiliary devices are available.

Taxiways.—Because it was generally agreed that main landing gear trends would be about the same as current jets, taxiway widths of 75 ft should be adequate. There was no definite indication regarding the need for shoulder stabilization particularly because it is quite probable that the engines will be clustered close to the center of the aircraft so that blast or ingestion should not be critical problems. Taxiway radii could very well be a problem depending on the configuration and wheel base of the gear. There was every indication that minimum desirable radii will be in the neighborhood of 400 ft. The addition of

a suitable fillet on the inside edge to widen the taxiway at the turn should take care of existing taxiways with smaller radii.

GROUND HANDLING

Apron Layout.—In general for any type aircraft the apron layout depends on ground maneuvering characteristics that, in turn, are governed by the aircraft configuration, landing gear geometry, and so forth as well as servicing requirements and methods of passenger loading and unloading. It is not expected that the supersonic aircraft, even if they are of the carnard-delta form, will present any unusual problems other than those occasioned by its longer length. For the longer lengths up to 200 ft the nose gear will probably be located up to 80 ft from the aircraft nose. This will result in a minimum turning circle or gate size for taxi-in taxi-out operation of 300 ft to 350 ft. If gates of these sizes cannot be arranged by using two existing gates the use of nose-in parking may be the answer. Standard wing tip taxi clearance of 25 ft should be adequate. Precise positioning on the apron under power should be just as feasible as with current jets.

Aircraft Servicing.—Desirable gate times for transit or through operations were considered to be 30 min with 1 hr to 2 hr for turnarounds. For transit operations fueling, will probably be the major limiting servicing activity, whereas for turnarounds cabin cleaning and galley servicing will probably control.

In view of the large quantities of fuel required, hydrant fueling will be a necessity. Fueling rates up to 1800 gpm were indicated. Existing fuel storage and hydrant systems with some modifications may suffice.

Ground electrical power requirements will increase with estimates ranging up to 200 KW of 400 cycle power.

New techniques of cabin cleaning that include the use of soil resisting materials, larger ash trays with vacuum disposal tubes, and built-in vacuum systems for rug cleaning will be utilized.

The use of auxiliary wheel drives for ground movement of aircraft was not indicated. Either taxiing under power or towing by tractor seemed to be preferred.

The development of improved in-flight air conditioning systems that would also serve on the ground was considered most probable. If necessary existing ground units could be used to supplement them.

Improved ground starting equipment capable of starting two or more engines simultaneously will be necessary. Otherwise with a possible 50 sec starting cycle per engine, up to 5 min will be required just to start six engines.

Blast fences where required, because of peculiar conditions, will have to be of stronger designs to withstand greater thrusts and will have to be higher as engines will be higher off the ground.

Exterior cleaning of aircraft surfaces will be important, because aerodynamic heating will tend to burn foreign matter into the surface.

Most manufacturers were of the opinion that automatic check-out facilities for aircraft systems would be available to reduce servicing time requirements and to assist flight engineers in their inspection and checking of aircraft prior to flight.

Passenger Handling.—The larger supersonic aircraft may have up to four passenger doors; this would help with loading and unloading greater numbers

of passengers. The use of loading bridge systems will be almost a requirement. Currently used nose-loading bridges for nose-in parking or the telescoping types for parellel parking can probably be modified to serve these aircraft. There was some indication that cabin floor heights might be as high as 14 ft to 15 ft which could be a problem in making use of present facilities. There was some indication that the mobile lounge method of passenger loading and unloading with the aircraft parking remote from the terminal building could be used to advantage. The success or failure of the Dulles experiment will probably provide the answer to this.

Baggage Handling.—The use of preloaded baggage containers mechanically loaded and unloaded into and out of the aircraft will be a definite requirement. Most airlines indicated that present systems of this type, although generally satisfactory, can stand further development.

FLIGHT OPERATIONS

Flight Planning.—Flight planning will have to be much more detailed than current practice. Ideally complete data covering exact take-off time, climb, cruise and descent profiles, approach and landing times should be determined in advance. Computers will, of course, be used for this planning. Engines will not be started until take-off clearance has been obtained.

Take-Off.—Take-offs will be similar to that used for today's jets except that speeds will be higher. Because of these higher speeds the effect of errors in rotation or lift-off speeds will be more pronounced.

Climb.—After take-off acceleration to a Mach of about 0.9 will be quite rapid. Climb rates will probably be in the 4,000 fpm to 8,000 fpm range to approximately 30,000 ft to 40,000 ft. The problems of passenger discomfort and poor forward visability due to steep climb angles will have to be taken into consideration. It is assumed that ATC problems will have been taken care of in flight planning. At this altitude transonic acceleration will occur and climb will be continued on up to cruising altitude which should be reached in 20 min to 30 min at about 250 miles to 300 miles from take-off.

Cruise.—Optimum cruise will be at a constant Mach number but not constant altitude. A stepped cruise procedure will probably be used that will also aid traffic control. Average cruising altitudes will probably be in the 70,000 ft to 80,000 ft range. Required altitude separation will probably be 2,000 ft, although this may change. Navigational and communications systems will require considerable improvement. At Mach 2 to Mach 3 speeds there will not be time for conventional systems.

Descent.—Descent will begin some 300 miles to 400 miles from destination and a decision on alternates will have to be made at this point. Again transition to subsonic speeds will have to be accomplished at altitudes above 30,000 ft. From this point on descent will probably be generally similar to today's procedures. Deceleration and integration with subsonic traffic will have to be precise. Holding when necessary should be at not less than 30,000 ft.

Landing.—As noted previously landing distances should be comparable to that required for present-day jets. Approach and landing speeds will be some-

what higher. Reverse thrust and improved braking systems should be capable of stopping the aircraft without other auxiliary means.

SUPERSONIC AIRCRAFT NOISE

General.—Current jet operations have shown that aircraft noise can be a serious problem. There is every indication that the public will, after a learning or educational period, accept noise up to certain limits. It is pretty much agreed that these limits must not be exceeded by any type of aircraft including the supersonics. The manufacturers representatives present at Montreal appeared to understand and agree with this and gave every indication that there were no undetermined problems involved.

Engine Noise.—Fortunately considerations such as thrust required for transonic acceleration to supersonic speeds as well as fuel economy requirements tend to favor the selection of turbofan engines. This is most favorable insofar as noise considerations are concerned. Ground taxiing noise may be somewhat higher than for present jets due to higher aircraft weights requiring greater thrust. Take-off noise should be no greater than that of current jets with the added advantage that a steeper climb-out will provide in getting more distance between the noise and airport communities.

Approach noise of current jets has been an unexpected but serious problem. Expected higher approach speeds of the supersonics does not favor any reduction. Engine design improvements and long intake ducts appear to offer the best possibilities.

Sonic Boom.—The sonic-boom problem has created more discussion than any other phenomenon of supersonic aircraft. Sonic booms are, of course, sharp pressure rises that occur when shock waves, produced by aircraft traveling at supersonic speed, make contact with the ground. Based on tests made by NASA such pressure rises of less than 1 psf are tolerable. Pressures above that figure can cause structural damage, the most common being window breakage. A characteristic that has not been fully understood is that sonic boom disturbances sweep the ground surface along the entire flight and the path of the boom can be as much as 60 miles or more in width. The intensity of the boom can be affected by the aircraft design, weight and operational procedures as well as atmospheric conditions. The altitude at which supersonic speeds are attained is perhaps the easiest variable to control. For that reason transition to and above Mach 1 is not planned below 35,000 ft.

CONCLUSIONS

Actually, the Montreal conference was not intended to provide enough factual information to permit drawing any definite conclusions. Its purpose was to point out, to all concerned with supersonic planning, areas that require further development.

The lack of definite answers to a majority of the problems discussed is not surprising when one stops to realize that total human controlled flight experience at Mach 2 or above amounts to only several hundred hours and at Mach 3 or above it is measured in minutes.

It is evident, however, that the aircraft companies have delved deeply into many of the problems involved and have provided answers to quite a few of

them. They seemed to be confident that further research studies and experimental flight experience will provide the remaining answers.

The airlines seem to be engrossed in subsonic jet operational and economic problems and hesitate to show interest that could be interpreted to indicate that they are seriously thinking of getting into the supersonic era. It appears as though it will be 1972 or later before supersonic scheduled airline service is possible.

DISCUSSION[a]

ROSS A. KNIGHT.[2]—These comments pertain to the statement that equivalent single wheel loadings on the supersonic transports may be as high as 120,000 lb.

Airport operators are happy to note that the supersonic transport will not require additional runway length, even though this is merely coincidental, brought about by the fact that the high thrust-to-weight ratio required to allow the aircraft to go supersonic automatically permits it to take off from existing runway lengths.

However, in place of a runway lengthening problem such as occurred in the early sub-sonic jet days, we now find that every operating pavement on the entire airport must be strengthened, because the present maximum equivalent single wheel loading required by the FAA is 100,000 lb, and very few civil airports even have that. Not only must the runways be strengthened, but also every taxiway, servicing apron, by-pass ramp, and so forth, that the supersonic transport will utilize.

It would behoove the airlines who order these aircraft (and after all, the manufacturers must produce what their customers want, or they won't sell any airplanes) to insist that the supersonic transport be designed to operate on existing pavement strengths, as well as existing runway lengths. If this is not done, one can picture a supersonic transport sitting out on the dry lake bed at Edwards AFB in a few years, all dressed up and no place to go.

RESPONSE.—This is a real problem; however, there will probably be only ten or twelve airprots in the United States that will be affected.

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[a] The full discussion from the floor was tape recorded, but for the sake of clarity and brevity the remarks were slightly condensed and, occasionally, paraphrased. In some cases the identity of the discusser could not be determined.

[2] Dir. Tech. Services, Airport Operators Council.

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LOCATION AND NUMBER OF EXIT TAXIWAYS

By Robert Horonjeff,[1] F. ASCE

SYNOPSIS

Since World War II the techniques of operations research have been applied to many fields of endeavor. More recently these techniques have been applied to the evaluation of airport configuration from the standpoint of aircraft traffic potential. This paper describes an effort in this direction. The past several years have witnessed a very rapid rise in aircraft traffic at airports. Concern lest the airport be the limiting factor in the traffic-handling capacity of the airport-airways system prompted the Research Division of the Bureau of Research and Development, Federal Aviation Agency, to sponsor a study, the objectives of which were (a) to determine the operational feasibility of high-speed exit taxiways as a means of increasing the acceptance rate of a runway, and (b) to determine the proper location of the exits along the runway. The operational feasibility of high-speed exits was evaluated by live tests with aircraft. A report was submitted to the Federal Aviation Agency covering the results of these tests.[2] A second and third report were prepared and submitted to the Federal Aviation Agency covering an analysis for locating exits,[3] and applying this analysis for the recommendation of specific locations.[4] The pres-

Note.—Discussion open until January 1, 1962. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Air Transport Division, Proceedings of the American Society of Civil Engineers, Vol. 87, No. AT 2, August, 1961.

1 Prof. of Transp. Engrg. and Research Engr., Inst. of Transp. and Traffic Engrg., Univ. of California, Berkeley, Calif.

2 "Exit Taxiway Location and Design," by Robert Horonjeff, et. al., Inst. of Transp. and Traffic Engrg., Univ. of California, Berkeley, Calif., 1958.

3 "A Mathematical Model for Locating Exit Taxiways," by R. Horonjeff, et. al., FAA Special Study, Inst. of Transp. and Traffic Engrg., Univ. of Calif., Berkeley, Calif., 1959.

4 "Exit Taxiway Locations," by R. Horonjeff, R. R. Read, and Gale Ahlborn, Research Div., Bur. of Research and Development, Federal Aviation Agency, Inst. of Transp. and Traffic Engrg., Univ. of California, Berkeley, Calif., 1960.

ent paper summarizes the second and third report. Specifically, the task was to formulate a mathematical analysis for determining the exit locations that will enable a runway to accept the greatest number of aircraft per hour under given sets of conditions. Thus, acceptance rate is a key factor in determining locations of exits. Only landings were considered, although it was recognized that high-speed exits, by clearing landings quickly from the runway, will also aid in accelerating the release of departing aircraft.

INTRODUCTION

The primary purpose of this paper is to describe (1) the methodology for developing a mathematical analysis (referred to herein as model) for locating exit taxiways and (2) the application of the analysis for recommending the location of the exits. Such recommendations required the operation of the model under a variety of different conditions and the processing of the results in some orderly manner. Conditions will vary at each airport. Obviously, exits cannot be placed to meet all of the changing conditions; consequently, the factors affecting exit locations must be carefully analyzed in order to establish typical conditions that will reasonably serve the purpose.

Certain types of aircraft were selected which it was felt would comprise the bulk of the airline traffic at the nation's airports. These aircraft are:

1. Boeing 707-120	8. Convair 880
2. Boeing 707-320	9. Caravelle
3. Boeing 720	10. Fairchild F-27
4. DC-8 (domestic)	11. Convair 340
5. DC-8 (overwater)	12. DC-7
6. Electra	13. DC-6B
7. Convair 990	14. Super Constellation

Notably absent are small general aviation aircraft and supersonic transports. In the case of supersonic transports it was felt that sufficient information concerning their performance was not available to make positive recommendations concerning the location of the exits. Preliminary information obtained from the manufacturers indicates that the over-the-threshold speeds will be higher than those of present-day jet transports; consequently, the suggested locations of exits for the current jets may not suffice for supersonic transports.

The omission of small general aviation aircraft from the analysis has nothing to do with minimizing their importance but is due primarily to the lack of landing data for this type of aircraft. It must also be recognized that small aircraft are unable to negotiate turns at high speeds (60 mph), because the speeds at which they become airborne are so low.

A considerable amount of attention was given to the composition of aircraft populations to be used in the analysis. At first it was assumed that the populations at various classes of airline airports would vary, depending on whether the airport served long, medium, or short range aircraft. That is to say, an attempt was made to classify aircraft according to range; then, by examining the routes served by various classes of airports and the amount of traffic over these routes, typical aircraft populations were established for analysis purposes.

After consultation with several airlines it was soon found that classification of aircraft by range was not very satisfactory, because airlines were prone to interchange equipment to best fit the needs of their over-all service system. Thus, a DC-8 or Boeing 707 could be used on short, medium, or long range routes. In view of this, it was decided to include populations in which the proportions of aircraft types varied widely, rather than to attempt to assign specific aircraft populations to various classes of airports. As an illustration, large jet transports of the Boeing 707 and DC-8 class were considered as constituting as low as 10% and as high as 60% of the total aircraft population. Likewise, aircraft in the class of the Electra and DC-7 were also considered as comprising a small and a large percentage of the total population.

The mathematical analysis permits treatment of aircraft arrivals over runway threshold in three different ways: (1) fixed intervals of time, (2) fixed intervals of distance, and (3) variable intervals of time depending on the runway occupancy time of the preceding aircraft. For the determination of exit locations, the third arrival scheme was selected for reasons explained subsequently.

The exit locations suggested herein are based on a turn-off speed of 60 mph at sea level, standard atmospheric conditions, and no wind or slope on runway; they are as follows:

Aircraft Group	Distance from Runway Threshold, in Feet
1. For large turbo-jet transports (DC-8, Boeing 707-120, 220, 320, Boeing 720, Convair 600, 800)	5,800 to 6,000
2. For four-engine, propeller-driven transports, and twin-engine turbo-jet transports	4,000 to 4,200
3. Twin-engine, propeller-driven transports and the larger twin-engine general aviation aircraft	2,600 to 2,800

The following corrections for airport elevation and temperature are suggested: The basic distances listed previously should be increased on the order of 3% for each 1,000 ft of airport elevation. The correction for elevation should be further corrected for temperature by increasing the distance to the exit by 2% for each 10° F rise above the standard temperature of the airport.

FACTORS AFFECTING THE LOCATION OF EXITS

A mathematical model is merely an expression of the operation of a system in mathematical terms. Its validity depends entirely on careful selection of the important factors affecting the operation being described. Hence, one must understand thoroughly the factors that affect exit locations. These factors are: (1) number of exits, (2) exit speed, (3) type of aircraft expected to use the airport, (4) the density of traffic during peak periods, (5) pilot variability, and (6) meteorological and geographical conditions at the airport. The effectiveness of the exits in this analysis is measured in terms of average runway acceptance rate. The idea is to locate the exits such as to yield the maximum

average acceptance rate for a fixed set of physical and operational conditions; the conditions being largely the six factors enumerated above. The resulting locations are referred to as optimum locations. Acceptance rates for locations other than optimum can also be determined. Thus, the gains achieved by placing exits at optimum locations can be compared with other locations.

BASIC MODEL

In order to develop a workable model, certain assumptions had to be made concerning the variables that would enter into its formulation. To begin with, although any number of exits or exit speeds can be handled, computer programs in this study were developed only for one, two, and three exits, and for three exit speeds: 15 mph, 40 mph, and 60 mph. Knowledge of the joint statistical distribution of time and distance from runway threshold to reach exit velocity is required. This distribution is affected by the previously cited factors: (3) aircraft type, (5) pilot variability, and (6) atmospheric conditions. An analysis of the limited available landing data indicated that the assumption of normality for this distribution would not be unreasonable. Thus, data on aircraft landings are necessary for the operation of the model.

The computation of the acceptance rate can be very simply expressed as

$$A_c = A_r \left(\frac{1}{1+q}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

in which A_c is the acceptance rate, A_r denotes the arrival rate, and the term $1/(1+q)$ is a correction factor in which q is the probability that an accepted aircraft will occupy the runway too long and cause the following aircraft to be waved off. The value of q depends on number and location of exits, aircraft population, arrival scheme, and so forth.

The number and location of high-speed exit taxiways enter into the computation through the correction factor. The value of the correction factor depends entirely on the probability q. Because the probability q has a range from 0 to + 1, the corresponding limits of the correction factor are 1 and 1/2. Thus, the upper limit of the acceptance rate is half the arrival rate.

The probability that an aircraft will miss its "natural" exit, that is, that the aircraft will be exceeding design speed at the first exit for which it has a positive probability of attainment, and the probability that the aircraft will take a greater time on the runway to turn off at its natural exit than the arrival separation interval will obviously depend on the location of the exit.

It should be noted that the acceptance rates as derived by the model are higher than are actually being experienced, because of the nature of the assumptions for aircraft arrivals. These acceptance rates are used for the purpose of comparing the effectiveness of exit locations and not for determining the acceptance rates of runways. However, these assumptions are valid for locating exits, and this was the primary objective of the project.

The probability q can be expressed as the weighted sum of the probabilities q_i that the individual class of aircraft will cause a wave-off. The weighting factor is determined by the proportion of each class of aircraft in the total population.

Summarizing

$$q = \sum_i p_i\, q_i \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

and

$$q_i = P_r\{T_i > \delta\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

in which $P_r\{T_i > \delta\}$ is the probability that the occupancy time T_i is greater than the time separation (δ) of aircraft on final approach to the runway and

$$T_i = \left\{\begin{array}{l}\text{Time required}\\ \text{to decelerate to}\\ \text{exit speed}\end{array}\right\} + \left\{\begin{array}{l}\text{Additional time to reach}\\ \text{first available exit taxi-}\\ \text{way or conventional exit}\end{array}\right\} + \left\{\begin{array}{l}\text{Time to turn}\\ \text{off into exit}\\ \text{taxiway}\end{array}\right\}$$

The first two terms of T_i are probabilistic, whereas the third is relatively constant.

A detailed deviation of the model is available.[3]

FACTORS INCLUDED IN THE DEVELOPMENT OF THE MODEL

Arrival of Aircraft by Type.—The order of aircraft arrival by type (whether, for example, a jet transport follows another jet transport or follows a propellor-driven craft) was considered as random, on the grounds that present procedures are on a first-come, first-served basis.

Distribution of Aircraft in the Population.—It was assumed that the arriving population of aircraft would consist of known percentages of each type of aircraft, and that these percentages would not change during the arrival period being studied.

Manner of Processing the Arrivals in the Air.—It was assumed that arrivals over runway threshold would take place in the manner approaching either (1) fixed time intervals, (2) fixed distance intervals, or (3) intervals of time equal to the anticipated runway occupancy time of the preceding aircraft plus a margin for error. These schemes assume a degree of control greater than that being exercised today. The arrival times were not treated as being statistically distributed, because the appropriate information applicable to the three assumed arrival schemes was not available. It was realized that variations in these intervals would occur, but such considerations was not included. The main reason for this was to permit the immediate development of a relatively simple model to which refinements could be added later if necessary. Because of limited time for the project, the model was operated for all three arrival schemes, but the locations suggested herein are based on scheme (3), modified slightly to include a margin of error in time intervals.[4] Although it is recognized that such an arrival scheme does not represent a true life situation, it does approach it, especially in VRF conditions when pilots tend to separate themselves near the runway threshold more on the order of scheme (3) than of scheme (1). It was also found that the optimum location for scheme (3) arrivals was also optimum for the two other schemes.

Other assumptions that had to be made were concerned with: (1) runway occupancy, (2) exit speeds, (3) wave-offs, (4) accidents, and (5) airport conditions.

Runway Occupancy.—The rule was adopted that the runway would be considered occupied from the time an aircraft was over the runway threshold until it was off the runway, and that only one aircraft (which had just landed) could occupy the runway at a time. It is recognized that this rule may not correspond with the actual case, because runway occupancy time from the standpoint of practical operations in all probability begins when the arriving aircraft is still

some distance ahead of the runway threshold. It is also realized that this real-life distance will vary among the different types of aircraft. It was felt, however, that the rule adopted is entirely adequate to the purpose.

Exit Speed.—It was assumed that an aircraft decelerates to exit velocity and then maintains exit velocity until it clears the runway. It was further assumed that an aircraft cannot turn off unless it has decelerated to exit velocity. Thus, if an exit taxiway were designed for 50 mph, an aircraft arriving at the point of turn off at 51 mph would miss the exit. This assumption is not entirely valid, because the geometric configuration of the taxiway permits a certain amount of leeway in speed. The assumption appears useable, as this leeway is probably not more than 5 mph.

Consecutive Wave-offs.—It was assumed that an aircraft that had just landed could cause the next aircraft to be waved off if it (the first) took too much time on the runway to reach an exit taxiway. However, the first aircraft would never take so much time so as to cause two consecutive wave-offs. This assumption was based on the study of the decelerating characteristics available for the types of aircraft included in this study and on the assumed average runway length of 10,000 ft. Thus, if an accepted aircraft fails to achieve the last high speed exit, it must go to the end of the runway, and the total occupancy time will not be so great as to cause two consecutive wave-offs. This assumption permits the model to be independent of the particular runway characteristics and of the particular operation chosen by the pilot to clear the runway.

Accidents.—It was assumed that no accidents would occur.

Conditions at the Airport.—It was assumed that there would be no change in surface temperatures or wind conditions at the airport during the period of arrivals being studied. No consideration was given to the minimum separation of aircraft on final approach to minimize the effects of turbulence by the creation of wing-tip vortices.

TYPE OF INFORMATION DERIVED FROM OPERATION OF THE MODEL

The general relation between arrival and acceptance rates for a given set of conditions is shown in Fig. 1. The straight line indicates the situation that would prevail on an ideal runway capable of accepting all aircraft.

Computed acceptance rates for any given set of conditions will, at any given arrival rate, be less than the ideal. This is so, even at very low arrival rates, because theoretically there will always be some chance of a wave-off, inasmuch as the distances and times for aircraft to reach exit speed are assumed to follow normal distributions. As a practical matter, however, the difference between computed and ideal values is so small over a considerable range of arrival rates that the two lines may be regarded as coinciding up to some value where the computed "real" rate begins to break away sharply from the ideal. After the two lines diverge, the ordinate to the computed line is the average acceptance rate; and the ordinate from the computed line to the ideal line is the wave-off rate, as indicated in Fig. 1 by the example for arrival rate x_b.

In operating the mathematical model, it is possible, for a fixed set of conditions, to determine an acceptance rate that corresponds to a selected percent wave-off, such as the point lying above x_a.

From a practical point of view, the designer would probably consider as acceptable some range of percentage of wave-offs between specified limits. In

this study the limits were arbitrarily chosen as 0.5% and 1% wave-offs, and the region between these limits is referred to as the balance region. Most of the comparisons made are for values obtained in the balance region.

Again, from a practical point of view, it must be recognized that the pilot has some leeway in making adjustments in braking on the runway. Thus, the setting of a very low percentage of wave-offs may not be too realistic for establishing exit locations.

Whatever percentage of wave-offs that one decides to use, the balance region is of special interest to the designer, because it, in effect, represents situ-

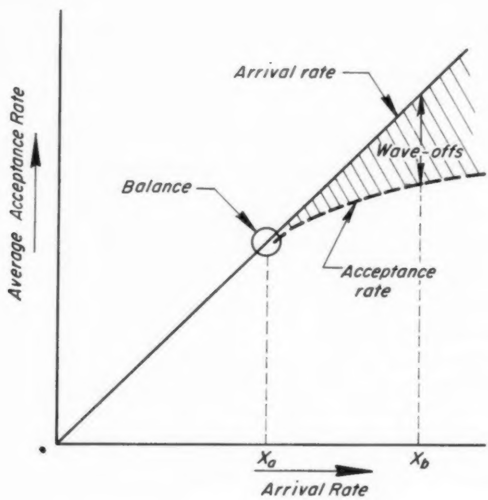

FIG. 1.—GENERAL RELATION OF AVERAGE ACCEPTANCE RATE AND ARRIVAL RATE

ations where the runway is loaded to capacity. That is, at lower arrival rates the runway is able to accept virtually all arrivals, but at higher arrival rates the percentages of wave-offs become objectionably high.

OPERATION OF THE MODEL

The operation of the model requires the selection of five principal inputs, namely, (1) aircraft population, (2) landing characteristics of aircraft (distribution of distance and time to reach exit velocity), (3) the manner in which aircraft arrive over runway threshold, (4) exit speed, and (5) the percentage of landing aircraft that will be unable to land because the runway is occupied by a preceding aircraft. This has been defined as a "wave-off." The basis for selecting each of these inputs is described subsequently.

Aircraft Population.—A detailed examination of the landing characteristics of various classes of transport aircraft revealed that they fall into three groups

(hereafter designated A, B, and C): (A) large turbo-jet transports, (B) four-engine, propeller-driven transports and twin-engine, turbo-jet transports, and (C) twin-engine, propeller-driven transports and the larger twin-engine, general aviation aircraft. (Landing characteristic is defined as the time and distance required by an aircraft to reach an exit velocity of 60 mph from runway threshold.)

It is very difficult to predict the composition of an aircraft population at an individual airport, particularly at a peak period of traffic. The composition varies considerably, depending not only on the routes flown, but also on the season of the year, how the flight equipment is used by a particular airline, and many other factors. Accordingly, the approach taken herein was to include a wide range of each of the three groups of aircraft and to see what happened to the exit locations. As inputs into the model, the percentages for each aircraft group were shown in Table 1.

TABLE 1.—AIRCRAFT POPULATIONS USED IN COMPUTATIONS

Percentage of Each Aircraft Group								
A	B	C	A	B	C	A	B	C
10	45	45	45	10	45	45	45	10
20	40	40	40	20	40	40	40	20
30	35	35	35	30	35	35	35	30
40	30	30	30	40	30	30	30	40
50	25	25	25	50	25	25	25	50
60	20	20	20	60	20	20	20	60

TABLE 2.—DISTANCES AND TIMES TO REACH EXIT VELOCITY OF 60 MPH

Parameter	Aircraft Group		
	A	B	C
Mean distance to reach exit velocity of 60 mph, in feet[a]	5400	3700	2400
Standard deviation, in feet	450	350	300
Mean time to reach exit velocity of 60 mph, in seconds[a]	32.4	25.1	18.1
Standard deviation, in seconds	3.0	2.5	2.5

[a] All distances and times are from runway threshold.

It will be noted from Table 1 that each specific aircraft group (such as A), is varied from 10% to 60%, the remainder of the percentage being equally distributed between the remaining two groups.

Landing Characteristics of Aircraft.—For each aircraft in the population, the mathematical model requires as input data the statistical distribution of distance and time from runway threshold to reach exit velocity (60 mph). It was, therefore, necessary to examine the landing characteristics of each type of aircraft and to ascertain how much similarity there was among the types. As a result of the analysis it was found that for all practical purposes the aircraft landing characteristics fell into three distinct groups corresponding to

the groups previously designated as A, B, and C. This meant that three distributions were sufficient to operate the model. The statistical parameters of these distributions are as shown in Table 2.

These parameters were estimated by (1) extracting information from observed landing data and (2) computing the time and distance to reach exit velocity (60 mph) from aircraft-performance data furnished by manufacturers and airlines. It was necessary to supplement the observed data with computations, because the observations did not include all of the aircraft that will be in service within the next year or so. Computations were also made for aircraft for which observations were available. This supplied a partial check on the validity of the method of computations.

The observations were derived from three sources, as follows:

1. The landing tests conducted by the United States Air Force at Wright-Patterson Air Force Base in connection with the exit taxiway study conducted for the Airways Modernization Board.[2]
2. Observations made by the Airborne Instruments Laboratory at New York International Airport for the Bureau of Research and Development, Federal Aviation Agency.[5]
3. Observations made by a research group in Germany.[6]
4. Observations made by the Franklin Institute at Washington National Airport.[7]

From these sources a summary of the times and distances taken by various aircraft to reach an exit velocity of 60 mph was tabulated (Table 3).

The average distance and time for a landing aircraft to achieve exit velocity after crossing the runway was also computed by assuming threshold speeds, average distances from threshold to touchdown, and average deceleration rates after touchdown. Operating threshold speeds were obtained after consultation with the operators. The following average touchdown distances were chosen for the analysis.

1. 1,600 ft for the larget turbo-jets;
2. 1,500 ft for the smaller turbo-jets;
3. 1,200 ft for four-engine propeller-driven transports and twin-engine jets; and
4. 1,000 ft for twin-engine propeller-driven transports.

As to rates of deceleration, analysis of aircraft-landing data indicate that rates of deceleration after touchdown vary over a rather wide range and are influenced by such factors as available runway length, condition of the pavement surface, visibility conditions, wind location of exits, and destination of the aircraft at the ramp. The tests at McClellan Air Force Base and at Wright-

5 "Runway Characteristics and Performance of Jet Transports in Routine Operations, prepared by the Airborne Instruments Lab. for the Federal Aviation Agency, Inst. of Transp. and Traffic Engrg., Univ. of California, Berkeley, Calif., Report No. 5791-15, Vols. I, II, March, 1960. Also, "Runway Characteristics and Performance of Selected Propeller-Driven Aircraft in Routine Operations," Report No. 5791-15, Vol. III, April, 1960.

6 "Belastungszeiten Von Start-Und Lande-Bahnen Im Hinblick Auf Die Anordnund Und Notwendigkeit Von Schnellabrollwegen," Arbeitsgemeinschaft Deutscher Verkehrsflugäfen, Stuttgart Airport, Stuttgart, West Germany, January, 1960.

7 "Radar Mesaurements of Approach and Landing," by Alfred A. Jeschomek, Characteristics of Transport Aircraft, Report I-2185-3, The Franklin Inst. Labs. for Research and Development, Philadelphia, Pa.

Patterson Air Force Base indicate that an average deceleration somewhere between 4 ft per sec per sec and 5 ft per sec per sec was comfortable to passengers and for the pilot when braking on a wet pavement surface. These values were confirmed by observations of landings at New York International Airport[5]

TABLE 3.—SUMMARY OF OBSERVED AIRCRAFT LANDING CHARACTERISTICS

Aircraft Types	Sample Size	Distance and Time to Decelerate to 60 mph				Average Touch-down Dis-tance, in Feet	Average Runway Deceler-ation, in Feet per sec-ond per second	Source[a]
		Distance, in feet		Time, in seconds				
		Aver-age	Stand-ard devia-tion	Aver-age	Stand-ard devia-tion			
B-707[b]	61	5325	886	31.8	5.1	1623	5.5	A
KC-135	10	7092	517	41.3	2.3	1838	4.1	C
Caravelle	10	4274	568	-	-	-	-	E
Constellation	13	3668	546	34.1[c]	-	1319[d]	-	E
Constellation	18	3717	666	27.5	4.5	1067	3.7	D
C-121	10	3428	394	22.3	2.8	1573	5.0	C
DC-7	20	4162	926	29.0	5.8	-	4.0	B
DC-6/7	3	3842	-	35.1[e]	-	1347[f]	-	E
DC-6	22	3703	922	25.2	5.5	1183	4.7	D
DC-4	3	3832	-	34.8[g]	-	1300[h]	-	E
Electra	20	3752	572	25.2	3.6	-	4.6	B
Convair Viscount	8	3857	536	32.5[i] 31.6[k]	- -	1382[j] 1175[l]	- -	E E
Convair Viscount	20	3973	771	29.3	5.6	-	3.8	B
Convair	10	3560	1075	25.0	6.4	842	5.1	D
C-131	10	3726	200	25.6	1.65	2020	5.0	C

[a] Sources:

A. "Runway Characteristics and Performance of Jet Transports on Routine Operations," Airborne Instruments Lab. Report No. 5791-15, Vols. I, II, March, 1960.

B. "Runway Characteristics and Performance of Selected Propeller Driven Aircraft in Routine Operations," Airborne Instruments Lab. Report No. 5791-15, Vol. III, April, 1960.

C. "Exit Taxiway Location and Design," by Robert Horonjeff, Et al., Inst. of Transp. and Traffic Engr., Univ. of California, Berkeley, Calif., 1958.

D. "Radar Measurements of Approach and Landing Characteristics of Transport Aircraft," by Alfred A. Jeschonek, Report I-2185-3, The Franklin Inst. Labs. for Research and Development, Philadelphia, Pa., 1952.

E. "Belastungszeiten Von Start-Und Lende-Bahnen Im Hinblick Auf Die Anordnund Und Notwendigkeit Von Schnellabrollwegen,' Arbeitsgemeinschaft Deutscher Verkehrs-flugäfen Stuggart Airport, Stuttgart, West Germany, January, 1960.

[b] Includes several DC-8 observations. Values indicated computed from the following number of observations, [c] 31, [d] 39, [e] 53, [f] 31, [g] 40, [h] 47, [i] 134, [j] 105, [k] 94, [l] 97. Larger sample sizes were available for the specific parameters indicated.

and at Washington National Airport where the average deceleration rates ranged from 3.7 ft per sec per sec to 5.5 ft per sec per sec. Actually, transport aircraft are capable of decelerating at a much more rapid rate than indicated by these values. Thus, a margin of safety is provided in the event of an emergency.

After reviewing the landing observations and taking cognizance of the fact that braking devices are being improved, it was felt that a value of 5 ft per sec per sec would be a reasonable value to use in the analytical solution.

The results of the computations are shown in Table 4. A comparison of the data in Table 4 with the data in Table 3 indicates that the observed distances and times to reach an exit velocity of 60 mph are generally larger than the computed distances. This is probably due to the fact that the available runway length, the locations of exit taxiways, and in some cases traffic volumes precluded the necessity for the pilot to achieve deceleration rates as high as 5 ft per sec per sec. However, except for a few types of aircraft, there is sufficient agreement to justify the use of the analytical approach; such an approach had to be used for the jets yet to be placed in service.

TABLE 4.—SUMMARY OF CALCULATED LANDING CHARACTERISTICS

Aircraft Type	Manufacturer	Average Landing Weight in Pounds	Stall Speed, in Knots[a]	Threshold Speed, Knots	Touchdown Speed, in Knots	Touchdown Distance, in Feet	Distance to 60 mph, in Feet	Time to 60 mph, in second
F-27	Fairchild	36,000	71.0	97.5	86.5	1000	2360	18.0
CV-340	Convair	42,000	73.0	100.0	87.5	1000	2415	18.3
DC-6B	Douglas	82,000	80.0	109.0	97.0	1200	3100	22.0
L-1049G	Lockheed	105,000	83.0	113.0	100.5	1200	3301	23.0
DC-7	Douglas	90,000	84.5	115.0	101.5	1200	3359	23.2
L-188	Lockheed	85,000	88.0	119.5	108.0	1200	3728	25.0
Caravelle VI	Sud	88,000	86.5	117.5	107.5	1200	3740	25.1
DC-8 (Domestic)	Douglas	180,000	95.5	129.0	119.0	1600	4860	30.2
CV-880	Convair	125,000	98.0	132.0	122.5	1500	4990	30.7
CV-990	Convair	145,000	97.0	131.0	121.0	1600	5000	30.8
DC-8 (Overseas)	Douglas	193,000	98.5	133.0	123.0	1600	5160	31.4
B-720	Boeing	165,000	100.5	136.0	126.0	1500	5260	31.8
B-707,320	Boeing	189,000	101.0	137.0	127.0	1600	5410	32.4
B-707,120	Boeing	163,000	102.5	138.0	127.0	1600	5430	32.4

[a] Stall speed is for average landing weight.

Examination of the results in Table 4 indicates that insofar as distances and times to reach an exit velocity of 60 mph is concerned the aircraft fall into three distinct groups (as indicated by the division made in the table). Within each of these groups the spread in distance to reach exit velocity is approximately 600 ft and the spread in time is about 3 sec.

As stated previously, the model can take as inputs any number of statistical distribution of distances and times to reach exit velocity, but it did not seem necessary to input such a large number of individual aircraft types when there was this natural grouping of landing performance.

Therefore, it was decided to represent each group by a normal distribution of time and distance to reach exit velocity. The means for each group as shown in Table 2 are approximately the maximum values of distance and time for

each group shown in Table 4. The mean distances are 5,400 ft, 3,700 ft, and 2,400 ft. The mean times are 32.4 sec, 25.1 sec, and 18.1 sec.

To complete the statistical description the standard deviation for each group is required. From observations of landings previously referred to, standard deviations for various types of aircraft were computed. It was found that the standard deviations obtained from observations at New York International Airport[5] and Washington National Airport[6] were larger than from the tests made at Wright Air Development Center.[2] This is understandable for the observations at New York (observations at New York were not on the new landing runway 4R-22L) and Washington were influenced by local conditions in the way of available runway lendth, location of existing exits, and meteorological conditions. On the other hand, the landings at the Wright Air Development Center were controlled tests in which many of the variables that influence the landing operations were minimized.

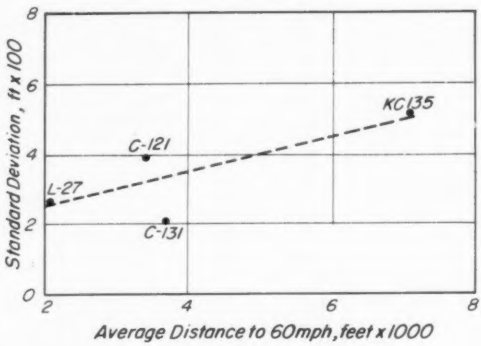

FIG. 2.—STANDARD DEVIATION OF DISTANCE REQUIRED TO DECELERATE TO EXIT SPEED, FROM WRIGHT TESTS

The observations made at New York and Washington were on runways where the exits were not located on the basis of the landing characteristics of any group of aircraft. Under such circumstances one would expect the standard deviation to reach exit speed to be larger than on a runway where the exits were located on the basis of the landing characteristics of the aircraft serving the airport. Consequently, it was decided to give greater weight to the Wright Air Development Center data: the standard deviations (distance) for each aircraft were computed and plotted against the mean distance required by the aircraft to reach 60 mph. A curve was fitted to the plotted points (Fig. 2). Such a curve relates standard deviation to the mean distance to reach an exit velocity of 60 mph. In this way the standard deviations shown in Table 2 were estimated.

Runway Arrival Schemes.—The manner in which aircraft arrive at the runway threshold must be described as an input into the model. As described previously, the model was developed for aircraft arriving at the runway threshold as follows: (1) fixed intervals of time (such as, 40 sec, 50 sec, and 60 sec),

(2) fixed intervals of distance (such as, 2 miles, 3 miles, and 4 miles), and (3) variable intervals of time depending on the occupancy time of the preceding aircraft.

After discussing the matter with the staff of the Bureau of Research and Development, it was decided to locate the exits on the basis of scheme (3). In scheme (3), landing aircraft are separated at runway threshold by the expected runway occupancy time of the preceding aircraft plus a margin for error. Let us call this the service time. Thus, if a Convair 340 was landing and was followed by a Boeing 707, the interval of time between the two would be less than if two Boeing 707's were following each other. Although it is recognized that such an arrival scheme does not represent a true life situation, it does approach it. In VFR conditions, pilots tend to separate themselves near runway threshold more on the order of scheme (3) than of scheme (1). In IFR conditions, current traffic control procedures require a minimum fixed-distance separation during final approach, which in the model is approximated by scheme (2). Yet scheme (2) when translated in terms of time, results in a variable time separation (when different types of aircraft are landing).

Exit Speed.—The entire analysis in this paper is based on an exit speed of 60 mph. It was decided that as long as aircraft were physically able to maneuver at this speed, there was no particular advantage to establishing locations at speeds less than 60 mph.

Observations taken by the Airborne Instruments Laboratory at New York International Airport on Runway 4R-22L, which is equipped with high-speed exit taxiways, reveal the following:

Type of Aircraft	Number of Observations	Average Exit Speed in Miles per Hour
Propeller-driven	27	54
Turbo-jets	8	57

These observations confirm the fact that aircraft are able to turn off at speeds on the order of 60 mph.

Wave-Offs.—A "wave-off" is defined as an arrival which does not become a completed landing because the runway is occupied at the time the landing is to be made.[3] In operating the mathematical model, it is possible, for a fixed set of conditions, to determine an acceptance rate that corresponds to a selected wave-off percentage. From a practical point of view, the aircraft operators would want to minimize the possibility of wave-offs so one percent was chosen for the operation of the model.

ANALYSIS OF RESULTS

Using the populations and landing characteristics cited previously, the model was operated first with three exit taxiways and aircraft arrival intervals based on shceme (3) arrivals. The results of this operation are presented in Table 5.

With the exit taxiways located at 2,660 ft, 4,000 ft, and 5,760 ft (which are at optimum) the service times for the three groups of aircraft A, B, and C were found to be as follows:

Group A -- 53 sec
Group B -- 43 sec
Group C -- 36 sec

It will be noted from Table 5 that the location of the exits are relatively independent of aircraft population. Of 18 aircraft populations listed, only 7 yield-

TABLE 5.—OPTIMUM EXIT LOCATIONS, 3 EXIT TAXIWAYS

Aircraft Population, Percentage of each Group			Optimum Locations,[a] 3-Exit Taxiways			Maximum per Hour Average Acceptance Rate
A	B	C				
10	45	45	2660	4000	5760	87.3
20	40	40	2660	4000	5760	84.5
30	35	35	2660	4000	5760	81.8
40	30	30	2660	4000	5760	79.4
50	25	25	2660	4900	5760	78.0
60	20	20	2660	4900	5760	77.5
45	10	45	2660	4900	5760	83.6
40	20	40	2660	4900	5760	81.5
35	30	35	2660	4000	5760	80.9
30	40	30	2660	4000	5760	81.2
25	50	25	3400	4000	5760	81.8
20	60	20	3400	4000	5760	83.7
45	45	10	2650	4900	5760	78.7
40	40	20	2660	4000	5760	78.1
35	35	30	2660	4000	5760	80.3
30	30	40	2660	4000	5760	82.5
25	25	50	2660	4000	5760	84.9
20	20	60	2660	4000	5760	87.4

[a] Distances are in feet from runway threshold, essentially sea level, standard temperature, no wind.

TABLE 6.—COMPARISON OF ACCEPTANCE RATES

Aircraft Population, Percentage of each Group			Average per Hour Acceptance Rate[a]	Maximum Average per Hour Acceptance Rate[b]	Percentage Difference of Maximum over Average
A	B	C			
50	25	25	77.0	78.0	1.3
60	20	20	74.8	77.5	3.4
45	10	45	80.4	83.6	3.8
40	20	40	80.6	81.5	1.1
25	50	25	81.5	81.8	0.4
20	60	20	81.8	83.7	2.3
45	45	10	76.1	78.7	3.3

[a] Computed for exit locations at 2,600 ft, 4,000 ft, and 5760 ft. [b] From Table 1.

ed optimum locations different from the majority. If we take these 7 populations and determine the average acceptance rates with the taxiways located at 2,660 ft, 4,000 ft, and 5,760 ft, the results are as shown in Table 6.

The data in Table 6 clearly indicate that if for these seven cases, the exits were located at 2,660 ft, 4,000 ft, and 5,760 ft from runway threshold in lieu of optimum (Table 5), the penalty suffered in terms of acceptance rate would be quite small. Consequently it was concluded that, for the wide variety of aircraft populations listed in Table 5, exits located at 2,660 ft, 4,000 ft, and 5,760 ft would be satisfactory.

Thus far, only three exits have been discussed. The question that is bound to be asked is: are three exits necessary or will two suffice? In order to answer this question, the model was operated with two exit taxiways with identical populations as for the three exits and the results shown in Table 7 were obtained.

TABLE 7.—OPTIMUM LOCATIONS, 2 EXIT TAXIWAYS

Aircraft Population, Percentage of each Group			Optimum Locations, 2-Exit Taxiways		Maximum Average Acceptance Rate, 2 Exits	Maximum Average Acceptance Rate, 3 Exits	Percentage Decrease in Acceptance Rate, 3 to 2 Exits
A	B	C					
10	45	45	4000	5760	74.0	87.3	15
30	35	35	4000	5760	72.4	81.8	11
60	20	20	4000	5760	70.0	77.5	10
45	10	45	2700	5760	74.7	83.6	11
35	30	35	4000	5760	71.8	80.9	11
20	60	20	4000	5760	75.0	83.7	10
45	45	10	4000	5760	72.7	78.7	8
35	35	30	4000	5760	72.2	80.3	10
20	20	60	2700	5760	78.7	87.4	10

[a] From Table 4.

TABLE 8.—OPTIMUM LOCATIONS WHEN ONE GROUP OF AIRCRAFT IS OMITTED

Aircraft Population, Percentage of each Group			Optimum Locations, 2-Exit Taxiways		Maximum Average Acceptance Rate
A	B	C			
0	50	50	2660	4000	91.8
50	0	50	2660	5760	82.1
50	50	0	4000	5760	74.0

From Table 7 it is evident that if the aircraft population consists of three distinct groups of aircraft, such as A, B, and C, the elimination of an exit is bound to decrease the acceptance rate of the runway; in this instance from 8% to 15%. If the reduction is considered significant, then the third exit would be justified.

Along these same lines, it was decided to determine the optimum location of the exits assuming one of the groups (A, B, or C) was not present in the population. The results shown in Table 8 were obtained.

From Table 8 it will be noted that the locations of the individual exit taxiways are identical to the locations shown in Table 5. This led to the conclusion that if an airport does not anticipate serving a particular group of aircraft (such as Group A) the thing to do is merely to omit the exit normally assigned to this group. For example, if an airport does not anticipate serving large jet transports (Group A) the exit located at 5,760 ft need not be constructed until jets use the airport.

TABLE 9.—COMPARISON OF ACCEPTANCE RATES: EXITS AT OPTIMUM LOCATIONS AND AT OTHER-THAN-OPTIMUM LOCATIONS

Aircraft Population, Percentage of each Group: A	B	C	Exit Locations, 3-Exit			Average Acceptance Rate	Percentage Difference[a]
10	45	45	2600	4000	5800	85.9	1.6
			2800	4200	6000	85.2	2.4
			Optimum[b]			87.3	
30	35	35	2600	4000	5800	80.8	1.2
			2800	4200	6000	80.1	2.1
			Optimum			81.8	
60	20	20	2600	4000	5800	74.3	4.1
			2800	4200	6000	73.5	5.2
			Optimum			77.5	
45	10	45	2600	4000	5800	79.3	5.1
			2800	4200	6000	78.7	5.9
			Optimum			83.6	
35	30	35	2600	4000	5800	80.0	1.1
			2800	4200	6000	79.2	2.1
			Optimum			80.9	
20	60	20	2600	4000	5800	81.0	3.2
			2800	4200	6000	79.0	4.5
			Optimum			83.7	
45	45	10	2600	4000	5800	75.7	3.8
			2800	4200	6000	74.7	5.1
			Optimum			78.7	
35	35	30	2600	4000	5800	79.4	1.1
			2800	4200	6000	78.6	2.1
			Optimum			80.3	
20	20	60	2600	4000	5800	85.8	1.8
			2800	4200	6000	85.4	2.3
			Otpimum			87.4	

[a] Percentage of acceptance rate corresponding to optimum location. [b] From Table 4.

In order to give the airport designer some latitude in fitting the exit taxiways into an existing airport configuration, it was decided to ascertain whether

a shift in distance of about 200 ft would have any material effect on acceptance rates. As a trial it was decided to locate the exit taxiways as follows:

For Group C aircraft	2,600 and 2,800 ft
For Group B aircraft	4,000 and 4,200 ft
For Group A aircraft	5,800 and 6,000 ft

Having selected a range for each location (such as, 2,600 ft to 2,800 ft) the model was operated to compare the acceptance rates for these locations with the rates for optimum locations shown in Table 4. The results are shown in Table 9.

It will be noted from Table 9 that the difference in acceptance rates for the range of locations selected and the rates corresponding to optimum locations is relatively small; consequently, it was concluded that a leeway of 200 ft in locating exits would be quite acceptable.

The question that has been asked is what would happen if the interval of time between arriving aircraft was held constant at 60 sec rather than variable. Our analysis indicates that all arriving aircraft could be comfortably accommodated with exits located at 2,660 ft, 4,000 ft, and 5,760 ft (Table 5). In other words, the optimum locations for aircraft arrival intervals based on the maximum expected runway occupancy time of each aircraft are also optimum for an arrival rate based on a fixed time interval of 60 sec.

INFLUENCE OF ALTITUDE AND TEMPERATURE

The exit locations suggested herein are essentially for (1) sea level conditions; (2) temperatures between 50° F and 60° F; and (3) relatively light wind. These are the principal environmental factors that can influence the ground touchdown speed of an aircraft and, hence, the distance it takes to reach exit velocity. Visibility is another factor affecting speed. When the visibility is poor, the over-the-threshold speeds tend to be higher than on a clear day. The presence of cross-winds tends to increase threshold velocities. After touchdown, the character of the pavement surface (snow or ice) has an influence on the amount of braking the pilot will apply.

It is evident that it is not possible to provide exits to take care of all the daily and seasonal fluctuations of environment at an airport. For example, the strength of the wind may vary considerably through the day and season of the year. (Headwinds tend to shorten the landing roll; tailwinds increase it.) For this reason it was suggested that the exits be located essentially for no wind conditions. Then, if a headwind or slight tailwind is present, the pilot could compensate for these conditions by adjusting his braking effort. This adjustment is possible because the exits were located on the basis of very comfortable ground deceleration rates of 4.5 ft per sec per sec to 5.0 ft per sec per sec.

The elevation of the airport is, of course, a fixed quantity that does not change from day to day. At higher elevations, the density of the air surrounding the airport is less than at sea level, which tends to increase the speed of an aircraft over threshold. Because there were no actual landings observed at high altitudes, it was necessary to estimate a correction on the basis of simplified calculations. Simplification is necessary because of the complex nature of the problem. The density of the air is primarily a function of pressure altitude rather than geographic altitude. Pressure altitudes tend to vary

with the season of the year depending primarily on the frequency of storms and other factors. However, the geographic altitude is still a reasonable indication of pressure, consequently it was assumed in the computations that the geographic altitude was equivalent to the pressure altitude.

Temperature is another factor that affects air density. Temperature was considered as an independent variable in the analysis. The formulas used to arrive at the suggested corrections for elevation and temperature are as follows:

$$V_T = V_{To} \sqrt{\frac{1}{\sigma}} \qquad (4)$$

in which V_{To} is the touchdown velocity on a standard day at sea level, V_T denotes the touchdown velocity at a specified altitude and air temperature,

$$\sigma = \frac{\rho}{\rho_o} \qquad (5)$$

in which ρ_o is the air density at sea level, standard day, conditions (59° F, 29.92 in. mercury), ρ denotes the air density at a specified altitude and for a particular temperature at that altitude,

$$\frac{\rho}{\rho_o} = \left(\frac{P}{P_o}\right)\left(\frac{T_o}{T}\right) \qquad (6)$$

in which P_o is the atmospheric pressure at sea level on a standard day, P denotes the atmospheric pressure at a specified altitude on a standard day for that altitude, T_o is the air temperature at sea level, standard day conditions, and T represents the air temperature at a specified altitude.

The touchdown speeds approximating sea level standard conditions were derived from observations of landings at the Wright Air Development Center and from manufacturers data. These speeds were corrected for altitude and temperature by using the foregoing relationships. In order to obtain the effect of elevation alone, the temperature of the standard atmosphere at a specified elevation was substituted for the term T. Having the corrected touchdown speeds, distances to reach an exit velocity of 60 mph were computed assuming a deceleration rate on the order of 5 ft per sec per sec. The distances so computed were compared with the corresponding distances at sea level, 60° F and no wind to arrive at an approximate correction for airport elevation as follows:

Increase the distance to the exit by 3% for each 1,000 ft of airport elevation.

A number of computations were made varying the temperature but holding the elevation constant to arrive at the following suggestion for temperature correction:

The correction for elevation should be further corrected for temperature by increasing the distance to the exit by 2% for each 10° F rise above the standard temperature of the airport.

CONCLUSIONS

As a result of digesting all of the information made available to this project and operating the model under a wide range of aircraft populations, the following conclusions were reached:

1. Although there are a large number of transport aircraft types using the nation's airports, based on their landing performance, they can be grouped essentially into three classes as follows:

a. Large turbo-jet transports (DC-8's, Boeing 707-120, 220, 320, Boeing 720, Convair 600, 800)
b. Four-engine propeller-driven transports and twin-engine turbo-jet transports
c. Twin-engine propeller-driven transports and the larger twin-engine general aviation aircraft

2. If the arriving aircraft are made up of all three classes of aircraft, the exit locations are virtually independent of the proportion of each class to the whole.

3. The number of exits required depends on the aircraft population. If the airport is to serve all three classes of aircraft, three exits are preferable to two. If the airport is to serve two classes of aircraft, two exits will suffice.

4. The location of an exit taxiway need not be fixed at a specific distance (such as optimum) from runway threshold because a certain amount of variation (in the neighborhood of several hundred feet) does not affect the acceptance rates a great deal.

5. Insofar as runway acceptance is concerned, the most desirable exit taxiway locations for the three classes of aircraft at sea level are as follows:

a. Large turbo jet transports	5,800 ft to 6,000 ft
b. Four-engine propeller-driven transports, and twin-engine turbo-jet transports	4,000 ft to 4,200 ft
c. Twin-engine propeller-driven transports, and the larger twin-engin general aviation aircraft	2,600 ft to 2,800 ft

6. In the future, should terminal traffic control equipment be successfully developed to sequence arrivals and departures at 60-sec intervals, the exit locations suggested herein will be able to accept substantially all arrivals at the runway.

7. A satisfactory rule of thumb to take into account airport elevation and temperature is as follows: increase the distance to the exit by 3% for each 1,000 ft of airport elevation. The correction for elevation should be further corrected for temperature by increasing the distance to the exit by 2% for each 10° F rise above the standard temperature of the airport.

ACKNOWLEDGMENTS

The writer wishes to acknowledge his colleagues R. C. Grassi, Robert Read, Gale Ahlborn, Derek Woolfall, Farnsworth Bisbee and Tadao Yoshikowa for their participation in the research which is the substance of this paper.

DISCUSSION[a]

FROM THE FLOOR.—If a runway is used only for landings, is it the author's basic assumption that the runway capacity can be in the neighborhood of 60 movements per hr?

RESPONSE.—Not exactly. The FAA Bureau of Research and Development visualizes a future possibility of bringing in aircraft at 60-sec intervals and they asked if a runway using the suggested exit taxiway locations would be capable of handling an arrival every 60 sec. The answer, for a 60 sec interval, is "Yes;" if the interval were reduced to 40 sec the answer would be "No."

FROM THE FLOOR.—In response to a request for information relative to the effect or use of grades in high speed exit taxiways, it was brought out that no published data exists on this subject and that at the two United States civil airports which have constructed (New York International Airport) or are constructing (Metropolitan Oakland International Airport) high speed exit taxiways, these taxiways are flat.

FROM THE FLOOR.—In response to a question as to whether or not the "drift-off" runway principle had been considered in the exit taxiway studies, Horonjeff stated that it had not. An FAA representative said that the Airports Division, Bureau of Facilities and Material, had conducted a very limited theoretical study of the "drift-off" runway configuration for the Bureau of Research and Development, the report of which has not yet been released.

NOTE.—The "drift-off" runway principle embodies a full-load bearing, 200 ft wide runway shoulder onto which a landing aircraft "drifts" after touchdown, thus clearing the basic runway for other traffic.

FROM THE FLOOR.—An FAA Airports Division spokesman stated that whereas the FAA agrees the maximum number of high-speed exit taxiways might be three, at certain airports with high very light aircraft population, there may be a requirement for a fourth exit taxiway, 1,600 ft or 1,700 ft from the landing threshold, for these very light aircraft. This turnoff could be almost a right angle one.

FROM THE FLOOR.—An FAA Airports Division representative cautioned that individual airports should make careful analyses before deciding to construct high-speed exit taxiways; certain airports may not ever need them and at others, where the need will not arise for many years, the money might well be put to better use at this time. This view was substantiated by Horonjeff.

FROM THE FLOOR.—The point was brought up that after an aircraft exits the runway at high speed and is still proceeding along a parallel taxiway at relatively high speed, a second aircraft could land farther down the runway, turn off at high speed on the next exit taxiway, and bring about a potential ground collision with the first aircraft at the intersection of the parallel taxiway and the second high speed exit taxiway.

RESPONSE.—This handling of high speed ground traffic at secondary intersections is a very real problem and will vary at each individual airport.

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[a] The full discussion from the floor was tape recorded, but for the sake of clarity and brevity the remarks were slightly condensed and, occasionally, paraphrased. In some cases the identity of the discusser could not be determined.

FROM THE FLOOR.—Paul Stafford described his studies indicating that a configuration that included an 800 ft straight-way between the high-speed exit taxiway and any secondary turn would permit deceleration to a complete stop if necessary.

FROM THE FLOOR.—In response to a question as to how fast pilots were actually leaving the runway via high-speed exit taxiways, conferees were informed that according to scope photography of the ASDE radar at New York International Airport, jet aircraft were turning off at 50 mph and up, passing them up only when going close to 60 mph.

Journal of the
AIR TRANSPORT DIVISION
Proceedings of the American Society of Civil Engineers

AIRCRAFT RUNWAY ARRESTING BARRIERS

By Apostolos H. Zonars[1]

SYNOPSIS

Aircraft runway arresting barriers are used as emergency devices by the Air Force. They consist of two elements: the engaging device and the energy absorber. Three types of engaging devices and four types of energy absorbers are described. Some quantitative values of kinetic energy, drag forces, and so forth, are shown for a fighter type and a bomber type aircraft.

INTRODUCTION

Sometimes it is advisable to define the basic function of a particular facility before any detailed discussion is entered. The function served by an aircraft runway arresting barrier can be simply stated: it provides an external means for stopping an aircraft on a runway. This function is useful both as an operational and as an emergency procedure. The Navy has been using barriers operationally ever since they have had aircraft carriers. Both the Navy and the Air Force are now using them as emergency safety devices.

The emergency type barrier is used as a last resort under the following conditions:

1. An overshot landing;
2. An aborted take-off; and

Note.—Discussion open until January 1, 1962. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Air Transport Division, Proceedings of the American Society of Civil Engineers, Vol. 87, No. AT 2, August, 1961.

1 Chf. Civ. Engrg. Group, Engrg. Branch, Engr. Div., Office of Civ. Engrg., Air Force Logistics Command, Wright-Patterson Air Force Base, Ohio.

3. Failure of internal braking devices such as brakes, drag-chutes, or thrust reversers.

On the other hand, an operational type barrier is used in every landing on an extremely short runway; the Navy's aircraft carrier is the classical example.

Regardless of the type of barrier, operational or emergency, two basic functions are performed: it engages an aircraft, then absorbs its kinetic energy, thereby bringing it to a stop. All barriers, therefore, have two elements, the engaging device and the energy absorber.

ARRESTING BARRIERS

The engaging device consists of two elements: a pendant that is basically a cable strung across the runway, and the aircraft engaging device that may be a hook mounted on the aircraft or the aircraft landing gear itself. The purpose of the engaging device is to engage the aircraft and transmit its kinetic energy to the absorber units.

The energy absorber transofrms, by some method, the kinetic energy of the aircraft into potential energy, generally in the form of heat.

The Air Force has levied a requirement recently that requires the barrier to accept aircraft at the rate of 2 per min. This requirement presents recocking problems for all types of absorbers and engaging devices. In addition, there are some types of absorbers that transfer energy into heat that raise the temperature of the hardware. For these cases heat dissipation becomes a problem. For example, if the energy absorbed in stopping a fighter aircraft is converted to heating 10,000 lb of water, it would raise the temperature of that water $6\frac{1}{2}$°F in 8 sec. For a bomber it would raise the temperature of the same amount of water over 90°F in $6\frac{1}{2}$ sec.

ENGAGING DEVICES

The pendant is a cable strung across the runway, anchored on each side of the runway to an energy absorber. One type of pendant (Fig. 1) is permanently located about 3 in. above the runway surface. This elevation is maintained by threading the cable through a number of 6-in. diam rubber disks, that, when in operating position, are about 5 ft apart. This type of pendant requires that the aircraft engaging device, a hook, be dragged along the runway when an engagement is necessary. To accomplish this the hook is similar to an overgrown tail skid (World War I vintage aircraft) made like a leaf spring so that it continually scrapes the runway. This "tail skid" is kept normally retracted near the tail of the aircraft, and released only when an engagement is desired.

Another pendant system (Fig. 2) consists of a webbing that stands like a fence across the runway. When an aircraft engages the webbing, it unfolds, throwing a cable (which had been resting on the runway) forward and upward so that the main gear is engaged. This fence is normally lying on the runway, and can be pneumatically raised to its operating position remotely from the control tower.

These two systems have a fair degree of reliability, particularly the low or supported cable, but they have their own disadvantages. The low cable re-

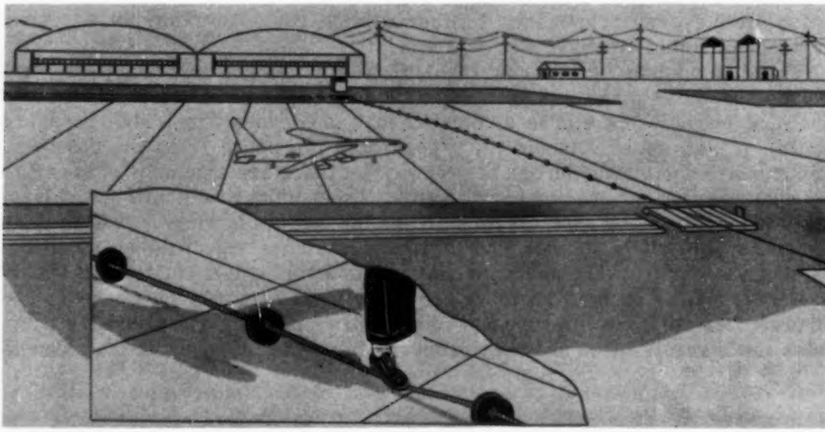

FIG. 1.—CABLE THREADED THROUGH DISKS

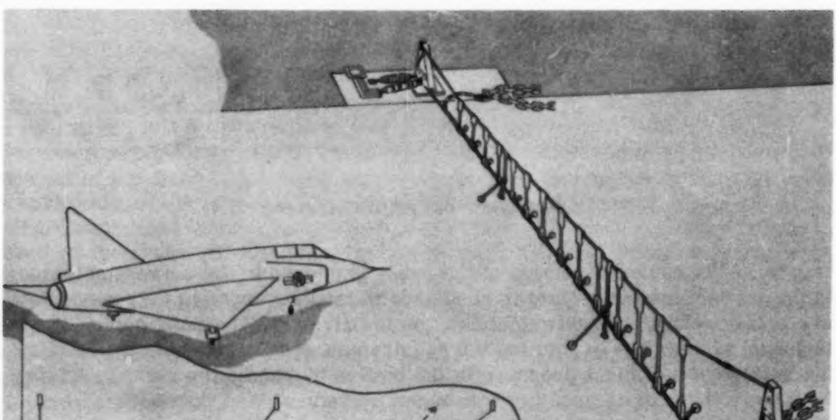

FIG. 2.—WEBBING ACROSS RUNWAY

quires a heavy retractable hook on the aircraft and several rubber disks must be replaced after every arrestment. The webbing system generally causes damage to the aircraft and invariably requires a complete new webbing installation after every arrestment. Neither system could be ready for a second arrestment within either 30 sec or 5 min.

There is another system now (1961) in its final stages of development that overcomes these disadvantages. Fig. 3 shows this system. The cable rests in a slot; beneath this slot is a chamber that is connected to a high-pressure bottle. A high-speed solenoid valve separates the bottle from the chamber. The cable is continuous across the runway but there are a number of separate air chambers, each with a separate valve. These units (chambers and valves) are 6 ft long. As the aircraft approaches the end of the runway it first rolls over a row of switch plates. The energized switches select the chamber and valve units that are to be energized and starts a timing computation. At least five and as many as nine chamber and valve units may be thus cocked. The aircraft then rolls over the second row of switch plates. The computer computes the aircraft speed and then properly times the actuation of the solenoid

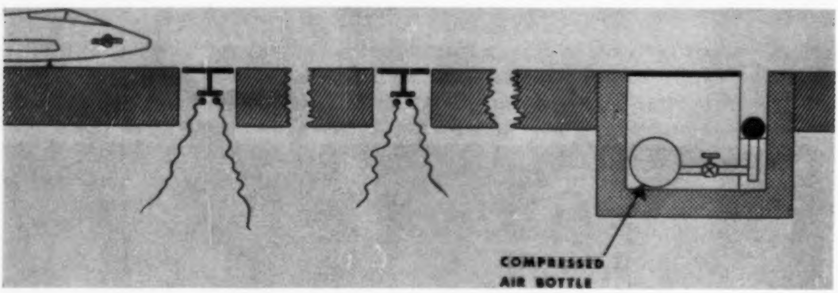

FIG. 3.—AUTOMATIC ARRESTING SYSTEM

valves. This causes a section of the cable to pop up to the correct height and at the correct moment (time is measured in milliseconds) to become engaged in a small, relatively lightweight hook on the aircraft. The most serious problem this system has in meeting the requirements of 2 arrestments per min is the buildup of sufficient pressure in the bottles to handle the next arrestment. It appears that this is possible with a compressor of less than 50 hp.

ENERGY ABSORBERS

There are four types of absorbers in use or contemplated for use by the Air Force. Any one of them may be used with any type of engaging device. Over a period of years there have been an almost uncountable number of absorption systems proposed. Many of these have been the usual assortment of ideas expounded by the same types that come up with perpetual motion devices. There are obviously many ways by which kinetic energy can be absorbed. The requirement that the barrier system must be capable of accepting aircraft at the

rate of 2 per min greatly reduces the number of absorber systems that are worth developing. As a matter of fact this stumbling block has not yet been completely hurdled. The systems now under development at least appear to have the capability to meet this requirement.

The absorber method now in use at a number of Air Force Bases consists of dragging chains over the runway. Fig. 4 shows this system. As the aircraft proceeds from left to right it picks up the pendant which, in turn, starts dragging the chains over the runway, the farther the aircraft moves, the more chain is brought into play. This system has been successful in that it has saved a number of lives and aircraft but it has several drawbacks, the chief of which is the practically impossible task of re-cocking the system in either 30 sec or 5 min. In addition, the drag force is lowest at the highest energy condition, and vice versa; it varies considerably between dry, wet and icy runways; and structural failure of a link could cause a crash that would be even worse than if arrestment had not been attempted (the Navy gives the Air Force its old anchor chains that were never intended for this type of loading).

An energy absorber in use at a few stations is called the water squeezer. Fig. 5 shows this system. It is a hydraulic energy absorber designed to absorb the arrestment energy of aircraft weighing up to 60,000 lb at engagement speeds up to 160 knots. It consists of two 1,400-ft long tubes buried in the ground, one on each side of the runway. The tubes are installed with a small slope with the lowest point near the arrestment end. The forward part of the tube is filled with water. Energy is absorbed by pulling a purchase cable and two loose fitting pistons through the tube. The cable absorbs the major portion of the energy, but the pistons maintain a nearly constant level of absorption after the cable slows down. Some of the disadvantages of the water squeezer include: the difficulty in changing the drag load (for different weight aircraft) and the amount of power necessary to re-energize the system.

An absorption system in late stages of development involves the application of friction on stainless steel leaves. Fig. 6 shows this system. The absorber consists of a pair of brake units that slide on steel tracks 200 ft long, one set on each side of the runway. Two 30-in. sheaves are mounted coaxially on a vertical axis and anchored at one end of the track. A brake carriage is positioned on the track end opposite the fixed sheaves. The brake carriage has two sheaves mounted coaxially and a hydraulically controlled brake unit. There are fourteen stainless steel tapes 210 ft long positioned in two stacks. These tapes pass through the brake unit and serve as the braking surface. A steel purchase cable is threaded in two loops between the stationary and moving sheaves. One end of the cable is attached to the carriage and the other end to the pendant. The sheave arrangment provides a 5 to 1 mechanical advantage, therefore, a 1,000 ft movement of the brake carriage. The chief disadvantages of this system are complexity and cost. The advantages, however, include automatically controlled drag load, and quick and low powered re-energization.

A fourth type of energy absorber (Fig. 7) basically utilizes the B-52 main gear brake, one for each barrier instead of one on each side of the runway.

The basic arresting barrier system consists of a pair of vertically oriented 60-in. diameter tape storage reels mounted on a common shaft with two aircraft disc type wheel brakes. Each tape reel accommodates 1,200 ft of spirally wound nylon tape 0.2 in. thick and 7 in. wide. The rotors of the brakes are connected to the dual tape reels. The reel and brake assembly is mounted on a welded steel frame that also supports the hydraulic control unit and the barrier retraction system.

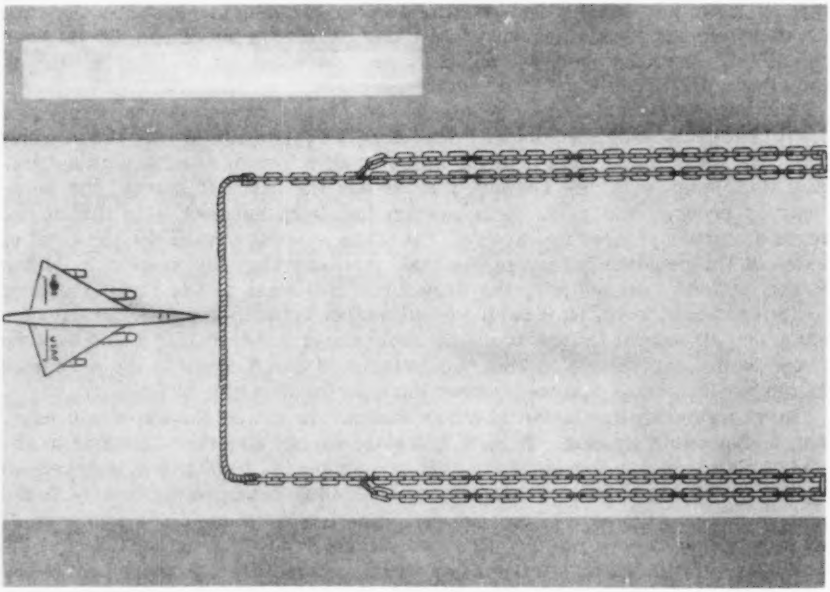

FIG. 4.—CHAIN ON RUNWAY

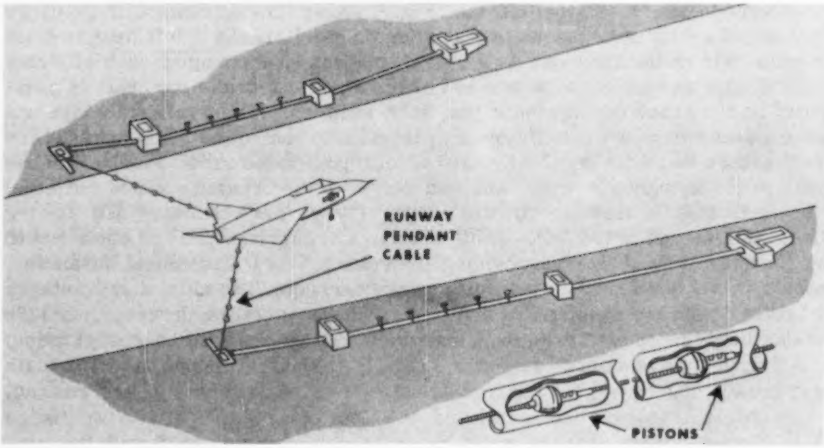

FIG. 5.—WATER SQUEEZER

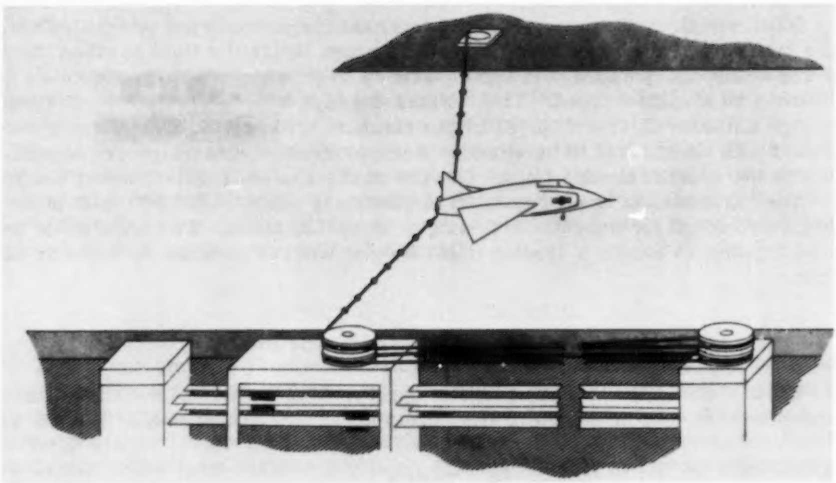

FIG. 6.—STAINLESS STEEL LEAVES

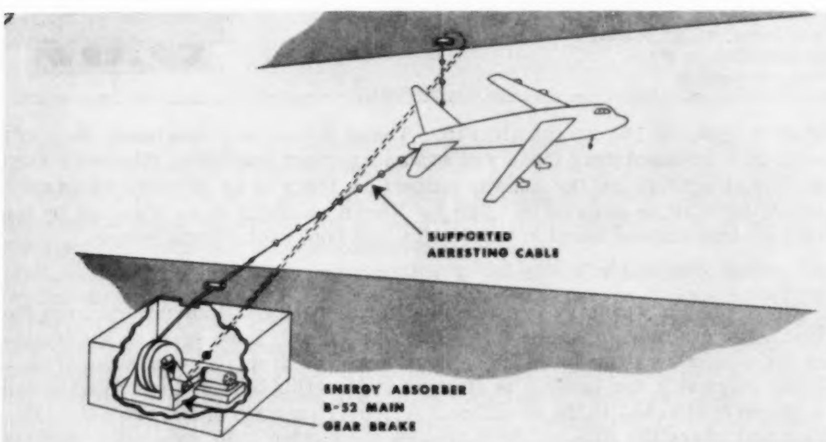

FIG. 7.—STEEL TAPE ARRESTING SYSTEM

Purchase tapes are conducted from the tape reels to sheaves or pulleys at the edges of the runway, with the tape going to the far side of the runway buried under the runway surface in smooth bore tubes. At the runway edges the tapes end in cowbell connectors.

When an aircraft engages the pendant, the purchase tapes are pulled out, the tape reels rotate and drive a hydraulic pump. Hydraulic fluid is taken from a reservoir and pumped through an orifice to produce brake pressure as a function of airplane speed. This brakes the tape stroage reels and, in turn, brings the aircraft to a stop. After the airplane is arrested, the system is rewound with an integral 10 hp electric motor or a motor-generator set, depending on the specific installations. Rewind of the system requires about 5 min.

The basic system has a capability of absorbing about 55,000,000 lb-ft of energy, or enough for a fighter traveling at about 150 knots. Two units could be tied together to handle a landing (light weight) bomber at about 80 knots or 90 knots.

PHYSICS OF THE ENERGY ABSORBER

Table 1 shows the values of kinetic energy, drag force, deceleration, time, and power to stop a 50,000 lb (fighter type, at 150 knots) and a 500,000 lb

TABLE 1

Item	Fighter 50,000 lb 150 knots	Bomber 500,000 lb 160 knots
Kinetic energy, in 10^6 pound-feet	49	560
Drag force, in 10^3 pounds	49	560
Deceleration, in g's	0.98	1.13
Time, in seconds	8	7 1/2

(bomber type, at 160 knots) aircraft. These values are idealized; they are based on a constant drag force and assume perfect conditions otherwise such as: the aircraft is on the runway centerline, there is no pitching or yawing, and the aircraft is stopped in 1,000 ft. These numbers were obtained by the familiar expressions found in all physics text books for kinetic energy

$$F = M A \qquad (1)$$

There are many practical aspects that force substantial deviations from the ideal. For example, considerable effort has already been spent on determining the dynamic response of the pendant when the drag force is suddenly applied. Normally, the pendant is changed in direction by a pulley so that it can be properly attached to the absorber. A stress analysis of the pendant at this point and where the aircraft hook applies the sudden load gets quite complex and difficult to handle. Each type of absorber has several points at which high magnitude acceleration can result in disastrous increase in drag force, or equally disastrous elimination of the drag force.

FUTURE

This brief discussion has not shown any methods, either for energy absorption or engagement, that are, at present, capable of handling high-speed bomb-

ers. There have been a number of successful B-47 arrestments at less than 100 knots, but only under the equivalent of laboratory conditions. As was noted previously, any physics text book will verify that some compromises are necessary if there is to be any success in the development of aircraft runway arresting barriers for high-speed heavy aircraft. Kinetic energy is still equal to $\frac{1}{2}$ M V^2.

There is, of course, continual product improvement development going on. One new energy absorber concept is presently being investigated. Basically, it consists of bending metal. Steel tapes are threaded through a series of rollers that result in tape unit stresses greater than the yield point. This cold working absorbs energy. A further development in this area is to use single strand high strength steel wire instead of the tapes. Component and model tests anticipate the ability for the prototype to handle speeds in excess of 300 knots. This is not for conventional aircraft.

IMPACT ON CONSTRUCTION

There are no real problems facing the facilities engineer with any of the engaging devices or absorbers. In some cases slots across the runway are necessary for the pendant systems. In all absorber cases (except for chains) some construction work is necessary along the sides of the runway for short distances. The most serious problems involve utilities and communications. Electric power must be brought in for the absorber units (except chains) and control tower operations require some type of communication with the system. The engaging device and the absorber are items of equipment, therefore, at least in the Air Force, that pose no problems to the civil engineer.

DISCUSSION

J. R. DART.[a]—It is of interest to review the possible civil applications and the Federal Aviation Agency Bureau of Research and Development program in the area of emergency arresting devices.

F. J. Rhody, F. ASCE, conducted tests, using a Convair 340, flying into touchdown and stopping in 1,400 ft without the use of brakes by hooking onto an arresting gear cable. Passengers were amazed to find, during a demonstration, that there was less sensation than when a plane reverses propellers during landing. Many were never actually aware when they engaged the barrier.

Records prove that most aircraft misfortunes occur on take-offs and landings with a large percentage occurring when the aircraft cannot stop within the length of the runway. This is not hard to understand when one considers the energy required to stop a modern transport weighing close to 300,000 lb and traveling at approximately 170 mph.

In the past, from Kitty Hawk until about 1950, this problem was overcome by simply leveling a little more land and as time passed, adding pavement. In

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[a] Major, Corps of Engrs., U. S. Army Bur. of Research and Development, FAA, Washington, D. C.

fact, some runways are over 2 miles long. It was during this period of growth that our present problem developed. Aviation became no longer just a sport but rather a serious business. Airports were no longer cow pastures but rather busy centers of trade and transportation. Cities have grown around them and not away from them. Land values about an airport have sky-rocketed with the speeds of the missle age. So, we have come to a point at which further expansion is almost impossible due to natural obstacles or economical reasons. Yet the airplane continues to grow, and the problem of stopping it grows with it.

The FAA has recognized this problem and has established a design standard for length of runways at sea level of 10,500 ft. It has asked aeronautical engineers to design accordingly.

The modern aircraft is a masterpiece of engineering and perfectly safe except in case of malfunction, which is rare; but this is always a possibility in any mechanical device. The use of suitable arresting gear would not eliminate all accidents, but would certainly reduce the number.

When the Agency undertook to study this problem we wnet immediately to the military, especially the Navy, who have had considerable experience in the field. We carefully studied all the existing gear and its possible modification to meet civilian needs.

To study the arresting problem, it was necessary first to establish the basic design requirements. So it was decided that it must be a single unit capable of stopping aircraft weighing between 50,000 lb and 300,000 lb with not more than 1 g decelerating force in a runout distance of not more than 2,000 ft. The operation and maintenance requirements must be the simplest possible to preclude an additional burden on Airport Operators.

Next, we divided the project in two component parts, the method of engagement and the energy absorber or engine.

In the engagement area there appears to be only two possible methods of getting hold of the aircraft, both of which have merit and also drawbacks. The first, and strictly an emergency method, would be snaring the landing gear with a cable that has the distinct advantage in that no modification is required on the aircraft. On the negative side, it is found that such engagements will seriously cut the gear struts and tend to shear off wheel doors, dive brakes, flaps, and other appendages. More important is the fact that this system requires precision timing or the cable will bounce off and the craft pass over it. Why? Because in the design of many jet transports the inside engines extend forward of the wheels and slightly below the top of the tires. However, the cable can be made to engage if raised at the precise moment, although this is a delicate operation.

This raises the question of method of elevation. The FAA has tried two methods and both required stanchions. In each case, the cable came up in the form of a sine wave that could engage one wheel and miss the other. Elevation was accomplished in the first tests, by a trigger cable that was mounted so that the nose wheel would pull the stanchions up. In the second tests, a sensor strip was used ahead of the main cable which tripped air valves to blow the stanchions up. Neither system proved very encouraging. The timing was tricky and required adjustment depending on the type and speed of aircraft.[3]

The other method of engagement is the old standard of the Navy, a tailhook, which is mounted on the aircraft just aft of the center of gravity. The first

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[3] Publication No. PB 161914, Offices of Tech. Services, FAA.

civil tests of the hook were accomplished by Rhody, as noted previously. A standard Navy AD hook was lengthened to 103 in. and mounted on a Convair 340. The hook was a rigid shank type that was controlled hydraulically by the pilot. Twenty actual engagements were attempted with only one miss, which was due to loss of hydraulic pressure.

In 1961, further tests of hook engagements will be made using a Sheaffer Spring Hook on a Boeing 720. This hook is performed in its down position and therefore requires no auxiliary equipment such as the hydraulic system. It is manually placed in the up position and held there by an explosive bolt, which can be fired by the pilot when it is desired to drop the hook.

At this time (1961), it is felt that the hook-type engagement is the best method although there are two serious problem areas to be worked out. One, is the weight, as the hook will add about 130 lb to an aircraft and this will mean the possible loss of one revenue-producing passenger. The other is the reliability of the single deck pendant or cable. To overcome the latter, some experiments are being conducted to find a method to connect several cables to a single energy absorber that will release all but the one actually engaged.

Now let us assume for the moment that the engagement problem has been solved and proceed to the arresting engine or energy absorber. We have established the requirements as follows: it must accept aircraft weighing from 50,000 lb to 350,000 lb, it must accept aircraft up to 130 knots, must not exceed 1 g deceleration, must not exceed a 2,000 ft runout, and must be compatible with either of the engagement devices.

There is, unfortunately, no such "animal," that is a proven engine. The military has and still is conducting tests on engines but do not have any requirement for one of this capacity. Thus, the FAA will have to study this problem alone. To further complicate things there is no test facility large enough to test this engine if it existed.

It is proposed, therefore, that there be constructed a test site that will have 300,000 lb dead loads accelerated to 130 knots, and with this, the FAA will test one of several possible engines.

In FAA research, many types of engines have been studied, and all of them have good and bad features. The simplest was the standard Navy anchor chain that has one of the smoothest decelerations because only one link at a time on each side is picked up. But where in a modern airport complex can we place the chain? It can't cross runways or taxiways, yet must be perpendicular to the direction of the aircraft.

There is the metal bender that disposes energy by dragging metal bands through a series of eccentric rollers that work the metal to its yield point first in compression and then tension. A wonderful machine - but what does one do with the mass of metal after the operation? It is also limited in size, but its originators are hard at work on the problem of increasing its capacity.

In the friction brake field there are several units, all very similar in principle. Most use nylon tapes on a drum.

Another proposal is a hydraulic system in which energy is dissipated by a turbine in the form of heat. There is a lot of merit in this proposal and the FAA will watch closely the testing by the military who have or will have soon, the prototype.

Compression of liquids or vapors has also been proposed as a method of energy absorption. One type, called a "water squeezer," is commercially available in capacity up to 60,000,000 lb-ft. It relies on a cable that is pulled

through a long tapered tube filled with water that is compressed by pistons mounted on the cable.

These are just a few of the many proposals. All have merit and are being very carefully studied to assure that we overlook nothing. The major criticism to date has been the complexity of the systems. The FAA would like an engine, that when installed, would require only quarterly inspection and very little maintenance.

Perhaps the most interesting proposal for civil engineers was an idea that combined both engagement device and energy absorber in one unit. It was proposed to build a 1,000 ft programed water pond at the end of the runway. To assist the FAA, the NASA conducted some very interesting scale model tests. From a strictly civil engineering viewpoint it would be cheaper to build a 1,000 ft overrun than the pond. Maintenance would also be expensive and scale tests showed a good possibility of aircraft damage. However, before abandoning this proposal it will be carefully studied by the FAA's system engineers.

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RECENT DEVELOPMENTS IN AIRPORT LIGHTING

By D. M. Finch[1]

INTRODUCTION

The lighting subjects that will be reviewed in this paper will include only those related to the visual requirements of a pilot during his initial and final approach for landing, and the touch-down and roll-out maneuvers on the ground that are part of the flight operations. Emphasis will be placed on the all-weather operations requirements, especially those conditions of restricted visibility. It is recognized that there are many other lighting problems in and around an airport, but these will not be discussed herein.

The approach and landing operation will be considered in three phases: (1) the visual requirements of the pilot while in the airspace near the airport, (2) the ground to air visual information transfer during landing, and (3) the visual guidance required for touch-down and roll-out. Much of this has been discussed previously.[2] This paper is intended to bring the subject up to date and to include the recent developments that have occurred in the past several years.

GENERAL REQUIREMENTS FOR VISUAL AIDS

Since the earliest days of flying, pilots have used ground references for navigation when approaching an airport, just as ships' officers at sea have used

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Note.—Discussion open until January 1, 1962. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Air Transport Division, Proceedings of the American Society of Civil Engineers, Vol. 87, No. AT 2, August, 1961.

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[2] "Airport Approach, Runway, and Taxiway Lighting Systems," by E. Walter and V. Roggeveen, Proceedings, ASCE, Vol. 84, No. AT 1, June, 1958.

landmarks. Non-visual devices, such as magnetic compasses, gyros, and electronic devices, are used to supplement the pilot's eyes while flying at altitude, and many instruments are used in situations wherein the aircraft is near the ground, but these devices are not generally used as substitutes for visual aids. The present navigational instruments begin to lose accuracy when the aircraft is within 150 ft to 250 ft from the ground. Except for very special and highly controlled flights usually involving military aircraft, it is necessary to have visual aids to bridge the gap at the final phase of landing and at take-off. In all probability, visual aids will continue to be required as long as manned-aircraft are used and windscreens are provided.

The pilot has need for visual aids in good weather as well as in bad weather and in the daytime as well as at night, but the requirements are different in each condition. A review of accident statistics[2] covering a 5-yr period revealed that over 95% of the total number of aircraft accidents occur during clear weather, and within 3 miles of an airport. While there were many causes of these accidents, a substantial number were attributed to the lack of visual references. Many others indicated pilot error as the cause, and, since a large portion of the pilot's information comes to him by way of his visual sense, pilot error can be at least partially assigned to lack of proper visual aids.

During the daytime enough light is always available to illuminate the area of the airport to an acceptable brightness level, but this does not assure good seeing conditions. For example, consider an airport enveloped by a daytime fog wherein the brightnesses are high but the contrasts are low. In this case it is necessary to have more than just a minimum amount of light. The light has to be utilized to develop contrasts and patterns that are meaningful to the pilot so that the improtant features of the airport can be identified and so that he can orient and control his aircraft in the airspace.

The seeing requirements are almost automatically met in clear weather conditions in the daytime, unless a deliberate attempt is made to camouflage the area (Fig. 1). The runway is always a long narrow strip with straight relatively open area. Paint markings have been developed and standardized to accentuate the threshold, the centerline, the edges, and to identify the runway. The outline can be easily located by flying over the field. Thereafter, the perspective view of the runway and the other identifying reference marks can be used for orientation when approaching the airport in the landing direction.

In clear weather in the daytime the pilot has an abundance of visual information, and by training and experience he can unscramble the transient visual pattern. The pattern will yield data on direction, distance, height, altitude, and rate of change of the aircraft with respect to these quantities. Experience has demonstrated that the most important elements of the airport which clearly define it for the pilot are the horizon, the edges of the runway, the threshold, and the centerline.

The FAA has developed the painting and marking specifications, shown in Fig. 2 (a), to clearly develop these elements.[3] At night, in both good and bad weather, and in reduced visibility in the daytime, the amount of visual information available to the pilot is very greatly reduced over that available in the clear weather, daytime scene (Figs. 2 and 3). It is essential in these attenuated visual situations to have the remaining visual pattern as clear and unambiguous as possible. The pilot may then see only a small portion of what he

3 TSO-N10b, Marking Serviceable Runways and Taxiways, FAA Tech. Standard Order.

would see in a clear, daytime landing, but what he does see should still have meaning to him and should permit him to make the required judgments necessary to complete the landing.

The pilot's problems in approach and landing must be understood by the airport designer so that the elements of guidance used in the clear weather, daytime situation may be artificially duplicated at night and in poor visual conditions. Therefore, the basic visual principles involved in landing an aircraft will be examined before the various components of the lighting system are considered.

AIRCRAFT LANDING OPERATION

The approach can be made from a straight-in direction extending outward 5 miles to 10 miles from the threshold, or it can be a circling approach. Each

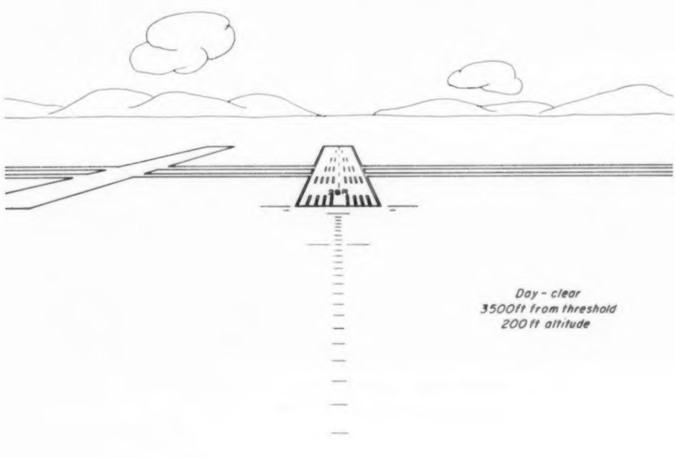
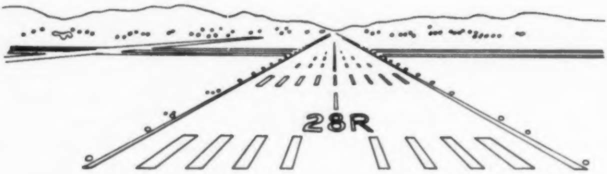


FIG. 1.—PERSPECTIVE VIEW OF AIRPORT RUNWAY

has its own requirements. The straight-in approach can be accommodated by the conventional approach lights, threshold lights and runway edge lights, as discussed subsequently. The circling approach is not adequately provided for by such lighting and needs additional runway outline lights to guide the pilot on his downwind run and base leg turn.

Present runway lights are not adequate for the circling approach because of their limited angular coverage.[4] Redesign of present runway lights for this purpose would seem to be out of the question, since about a tenfold increase in wattage would be required.[4] Specially designed circling guidance lights have proposed[4] and would be placed at 1,000-ft intervals along each side of the run-

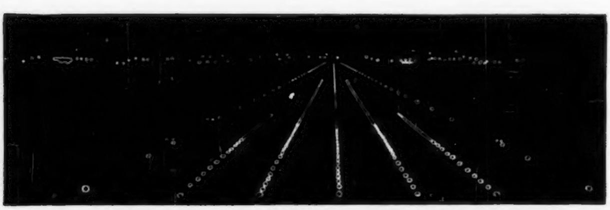
[4] "Visual Aids for Jet Aircraft," Report No. 6862, Natl. Bur. of Standards, U. S. Dept. of Commerce, Washington, D. C., June, 1960.



a Day – Clear, with standard markings

b Night – Clear, with standard lights.

c Night – Clear, narrow gage with centerline and standard edge lights.



d Night – Clear, with 5 – line pattern using inset button lights (45w to 3w) & standard edge lights.

FIG. 2.—RUNWAY AS VIEWED NEAR THE THRESHOLD ON GLIDE SLOPE—20 TO 60 FEET HIGH

a Day – **fog** , with standard markings

b Night – **fog** , with standard lights.

c Night – **fog** , narrow gage with centerline and standard edge lights.

d Night – **fog** , with 5-line pattern using inset button lights (45w to 3w) & standard edge lights.

FIG. 3.—RUNWAY AS VIEWED NEAR THE THRESHOLD ON GLIDE SLOPE—20 TO 60 FEET HIGH

way. The lights would be shielded from the straight-in approach direction but would be visible from all other directions around the airport at normal approach altitudes. It has been recommended[4] that the intensities should be maintained constant for Steps 1, 2, and 3 for the runway lights. The intensity distribution would vary from 100 cp at vertical angles of 20° to 60° to 5000 cp between 2° to 8° above horizontal, and at various azimuth angles the lights are designed to give the greatest visual assistance to pilots on the base leg of the approach during restricted visibility. The control circuits for the circling guidance lamps have been discussed in detail.[4]

The straight-in approach normally begins several miles from the end of the runway and may require electronic aids as well as visual aids for general orientation and identification of the runway. The initial approach will continue until the aircraft is brought into general alignment with the runway, and has been trimmed to a landing configuration. The aircraft will then have descended to a height of 200 ft to 400 ft and will then be 3,000 ft to 8,000 ft from the threshold of the runway. The final approach starts in this region. In reduced visibility the desired transition from instruments to visual aids will also occur during this interval. Thus, by either a circling or straight-in initial approach and by instrument and/or visual navigational techniques, the aircraft can be placed in location and altitude for the final approach. The airborne lights, airway beacons, airport beacons, and the other visual aids and lighting requirements for the flight operations up to this phase are important for navigation, safety and air traffic control, but they are not critical insofar as the airport designer is concerned. But the lighting and visual aids at the airport become increasingly important as the aircraft proceeds through the final phases of landing.

The aircraft may be considered as a transient point mass in a three-dimensional coordinate system in which it may have translation along the three coordinate directions and rotation about the three axes as it approaches a two-dimensional grid. If the axes are aligned horizontally, vertically, and parallel to the runway, the translation motions can be described as being in the lateral, vertical, or forward directions. The rotations are normally called pitch, yaw and roll for the horizontal, vertical and forward axes, respectively. During a landing, the pilot must control and coordinate all six degrees of freedom of the aircraft to bring it into coincidence with a desired path to the touch-down point on the runway.

The pilot has some flexibility in making an approach, but the desired glide path, the stall speed, and the recovery characteristics of the individual aircraft fall within reasonably narrow limits. The glide path and height, time and distance relationships during a typical landing are shown in Fig. 4. The desired glide path for most aircraft is about $2\frac{1}{2}°$, but this can vary from $1\frac{1}{2}°$ to 6°. The minimum over-the-threshold speed is usually specified by regulation as about 1.4 times the stall speed, so for most commercial aircraft the speed over the threshold will be about 150 mph. Just before final touch-down most pilots use a flare technique to reduce the impact load on the landing gear and to "feel" for the runway. Since the flare characteristics are affected by the reactions of both the aircraft and the pilot, the actual touch-down point may fall within a range of 0 to 3,000 ft from the runway threshold. For design purposes, the glide path is usually assumed to intersect the runway at a point approximately 1,000 ft from the threshold.

Regardless of the weather or time of day, the pilot needs certain basic information concerning the aircraft during landing; namely, translation information regarding alignment, height, distance, and rotation information regarding pitch, yaw and roll, plus rate of descent and rate of closure with the desired path.

ALIGNMENT GUIDANCE

The pilot must know where his aircraft is with respect to lateral displacement from the centerline of the runway. Most runways are between 150 ft to 300 ft wide and from 3,000 ft to 13,000 ft long. Thus, any runway is a long narrow ribbon when first seen from several thousand feet away. The predominant

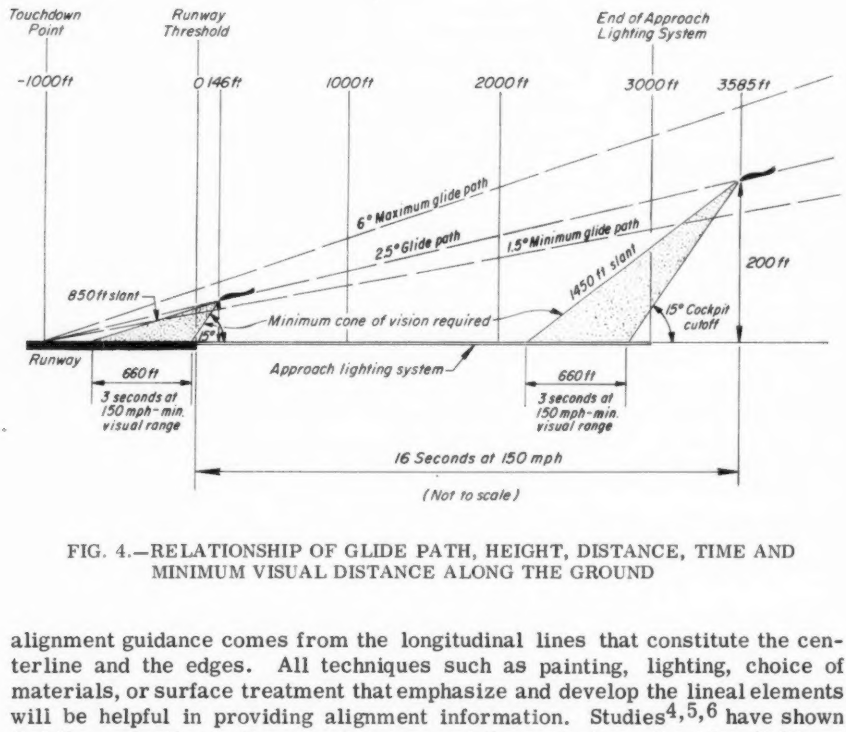


FIG. 4.—RELATIONSHIP OF GLIDE PATH, HEIGHT, DISTANCE, TIME AND MINIMUM VISUAL DISTANCE ALONG THE GROUND

alignment guidance comes from the longitudinal lines that constitute the centerline and the edges. All techniques such as painting, lighting, choice of materials, or surface treatment that emphasize and develop the lineal elements will be helpful in providing alignment information. Studies[4,5,6] have shown that the centerline in the approach zone and the centerline plus edge lights on

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[5] "Exchange of Views of the Principles Applicable to the Design of a Complete Lighting and Marking System," Visual Aids Panel Meeting, I. C. A. O., Montreal, November 16, 1960.

[6] "Surface Mounted Lights for Runway Guidance," by Dan M. Finch and Robert Horonjeff, Interim Report to the Federal Aviation Agency, April, 1959, and Final Report, June, 1960.

the runway are the most important basic visual elements to provide for alignment.

HEIGHT INFORMATION

If the weather is clear and if there is a familiar pattern of ground objects below and ahead, the pilot can use his psychological mental porcesses of recall and recognition to estimate his height with a surprising degree of accuracy. But the estimation of height above ground from visual cues alone is still one of the most difficult judgments for a pilot. When the terrain is monotonous, as over water, over desert land, over snow or unpopulated flat areas, or when the territory is unfamiliar, there are very few cues to use in estimating height. The pilot usually finds that his best source of height information down to 150 ft to 200 ft is the altimeter or the ILS indicator on the panel. At lower heights the uncertainty in the indications of these instruments will encourage a change from instrument flying to visual or "contact" flying.

The approach angle of approximately $2\frac{1}{2}°$ above the horizontal that is normally used during the landing operation places the aircraft 3,000 ft to 4,000 ft away from the runway threshold when the aircraft is 150 ft to 200 ft high. The flat, thin perspective view of the runway at 3,500 ft or more, as may be noted in Fig. 1, is not adequate as a basis for height judgment. The pilot needs additional foreground visual reference data, which he usually has in the daytime. The approach lights that extend 3,000 ft ahead of the threshold are useful for this purpose at night and in restricted visibility.

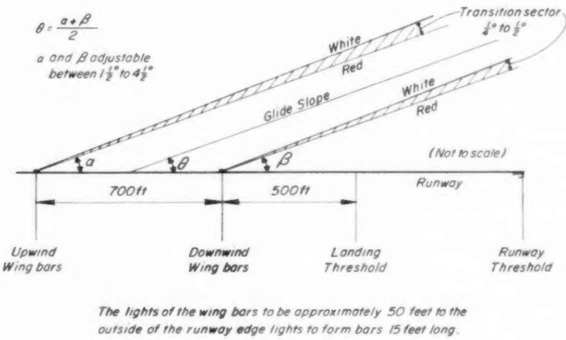
As the aircraft approaches from 4,000 ft to 1,000 ft ahead of the runway threshold, the perspective view of the edges and the foreground develop into a visual pattern that occupies a substantial part of the central visual field (Figs. 1, 2, and 3). If there are adequate reference lines in the longitudinal direction, a judgment of the change in the perspective angle with height can be made with considerable precision. As the aircraft nears the threshold at a height of 30 ft to 70 ft the change in the perspective angle can be used as a very good cue to height.

One objective in the lighting and marking system is to provide adequate lineal data so that a continuous perspective view of the approach area and the runway can be furnished to the pilot under all conditions of weather so that height information will be clear and precise.

VISUAL GLIDE SLOPE INDICATORS

As an aid in defining the desired glide path and thereby maintaining a safe height, several optical schemes using special lighting devices have been developed that permit the pilot to visually check his height from as far as 2 miles away from the touch-down point during an approach for landing. The several systems involve aligning the pilot's aircraft in the air with two or more sets of lights on the ground, so that a prescribed coded color combination of lights will show when the aircraft is on a satisfactory glide slope. The various systems provide a valuable check on the aircraft's height from any position where the visual reference lights can be seen. They are a useful adjunct to the visual aids system in clear weather, but obviously they are not helpful when the visibility is poor, because the aircraft may have to approach the threshold before

the lights appear. The system, known as the red-white VGSI has been generally agreed upon as the scheme for immediate adoption.[4] With this system, the pilot will see two pairs of lights symmetrically arranged on each side of the centerline near the touch-down point. If the first pair of lights is red and the second pair is white, the aircraft is on the proper glide path. If both groups of lights are red, he is too low, and if both groups are white, he is too high.



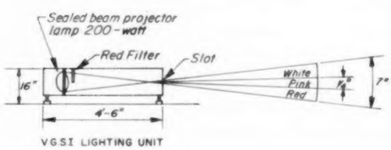


FIG. 5.—VISUAL GLIDE SLOPE INDICATOR AND DETAIL OF LIGHTING UNIT

Thus he knows where the aircraft is and what correction to make. The principle of operation is shown in Fig. 5.

DISTANCE ESTIMATION

During daytime conditons in clear weather, pilots will use known landmarks to estimate distance when making an approach. These can be quite adequate distance cues for pilots landing in familiar areas. When landing at unfamiliar airports, the pilot needs visual cues based on recall and association, for distance information. He can observe the relative sizes of objects, relative motion of objects, the scattering of the atmospheric haze, the blocking and shadowing of parts of the field, and the perspective appearance of far versus near objects. These are usually adequate in clear weather in the daytime, and the pilot has little difficulty in judging distance.

At night and in poor visibility the conditions are radically different, and the distance information may be very meager over the initial approach terrain. If

the airport and the aircraft are equipped with an instrument landing system (ILS or GCA) there will be instrument displays to give distance data to the pilot. These aids will begin about 4 miles or 5 miles from the runway threshold and are generally adequate to within about one mile from the threshold. From 4,000 ft ahead of and beyond the threshold the electronic aids for distance marking are not used at present, but it is desirable to have "distance to go" information. The pilot needs to know how far he has traveled along the runway at any instant and how many feet remain to the end of the runway. Conventional runway edge lighting and markings do not supply the needed distance information.

Several solutions to the "distance to go on the runway" have been proposed and tried. One scheme uses large illuminated signs placed alongside the runway every 1,000 ft from the end of the runway and numbered with the remaining distance in thousands of feet to the end of the runway.

This plan has not proved to be completely satisfactory because of the hazards, the problems of maintenance, the power requirements and the poor legibility due to the peripheral location.

Another plan for distance information suggested by the writer calls for a pattern fo longitudinal lines on the runway, beginning at the threshold, the number of lines decreasing 5 to 3 to 1 at selected distances down the runway (Figs. 2 (d) and 7). The five parallel lines making up the first zone would be arranged as a centerline, with two parallel lines spaced at 25 ft to 30 ft to each side. These lines plus the normal edge lights will clearly mark the threshold and will define the plane of the runway. They could extend to the nominal touch-down point which is 1,000 ft to 1,500 ft from the threshold. The pilot can easily judge with an accuracy of within several hundred feet when he is at the end of the first zone. The second zone, consisting of 3 lines formed by the centerline and one parallel line along each side, would continue for an additional 1,000 ft to 2,000 ft beyond the end of Zone 1. Military and commercial airports should have at least 3,000 ft to the end of Zone 2, due to the higher landing speeds and greater weight of the aircraft. General aviation airfields can use a shorter lineal pattern. As a general rule, Zone 2 should extend twice as far as Zone 1 and would mark the extreme end of the touch-down zone. The aircraft should have its wheels on the runway by the end of Zone 2 and would then be in the roll-out phase. A single centerline in Zone 3 plus edge lights will provide adequate guidance for roll-out along the runway.

Additional distance information along the runway can be derived from other cues, such as the taxiway turn-offs, signs and reference objects such as the radar buildings, transmissometer towers and lights, terminal lights and other objects that may be known to the pilot and that can be located when rolling at relatively slow speed.

A proposal has also been made[5] that small inset lights (button lights) could be arranged as numerals on the runway to indicate distance.

ROTATION CUES

An aircraft can rotate about three axes as previously noted. The fore and aft pitch rotation is normally adjusted for landing by the pilot at an early point in the approach. This setting, which is relatively constant, is determined largely by the aircraft aerodynamics. The yaw rotation or heading is also set

early in the landing operation to an angle that is principally controlled by the crosswind velocity. The final settings for these two rotations depend on visual information from the ground to the pilot, but in most landing operations these settings are made initially from information on the instrument panel. In the final phases of landing it is important to have visual information with which to monitor the adequacy of the pitch and yaw settings.

The principal visual rotation information required is that having to do with the horizon. This ocncerns the roll axis along the longitudinal centerline of the aircraft. In the daytime in clear weather there is always ample visual data for roll corrections provided that the pilot has forward and downward visibility. The ground terrain or the texture of a water surface, plus the natural horizon together with a frame of reference in the cockpit can give the necessary information on the angle of roll and is normally all that is required.

At night and in poor visibility weather (IFR) the natural horizon is not seen or is greatly reduced and should be supplemented by a suitable pattern of brightnesses on the ground. During the transition from viewing panel instruments to seeing the external visual aids, the weather can be so bad that the approach lights are the only lighting elements that are visible, and, therefore, these lights should give at least the minimum necessary roll information. This subject has often been discussed. At least two basic approach light systems have evolved and a third is on the way. The tow are known as the ALPA system (principally United States in origin) and the Calvert system (English in origin); Dutch system is emerging. The systems differ mainly in the number and extent of the cross bars intended to provide roll guidance. A plan view showing the three systems is given in Fig. 6. Since the Dutch system is somewhat of a hybrid compromise of the two others, it has been suggested[2] that it be called a CALPA or an ALPERT system. Extensive experience in the United States has shown that even the short segments of horizontal lines that are transverse to the line of sight give enough information on the angle of roll. The ALPA approach light pattern which is now the United States Standard Configuration A incorporates this feature by using rows of 5 lights each on 3 ½ ft centers to form transverse bars 14 ft wide, located at 100 ft intervals along the extended centerline of the runway for a total of 3,000 ft. When the approach lights are seen at long distances in clear weather they do not provide any appreciable roll guidance, but none is required since other cues can be used. At distances of 1 mile and less the transverse bars will appear as line segments about 0° - 10' of arc or more in width and some roll guidance is furnished, so that the initial trimming adjustments of the aircraft's attitude can be made. At 1,000 ft from the threshold a transverse bar 100 ft wide is provided in the ALPA system for further roll reference and as a distance marker.

APPROACH LIGHTING

The function of the approach lights has previously been reviewed. It may be noted that they should (1) help to identify the airport and the particular runway, (2) furnish alignment guidance, (3) provide some height information, (4) indicate approximate distance, and (5) furnish roll information when the aircraft is relatively close. All this information can be easily supplied during clear weather and even in present minimum IFR weather by any of the ap-

proach lighting systems now in current use. There have been numerous suggestions on how to improve the approach lights, but, in general, the basic requirements are met by the ALPA, the Calvert, or the Dutch system in all weather down to about 1 mile Runway Visual Range.

It is when we start to consider landing operations at zero ceiling and below about ½ mile visual range that the approach lights need crafeul consideration. The first lights to be seen are those at the end of the approach light pattern. The aircraft is relatively high and the slant distance to the first light is quite

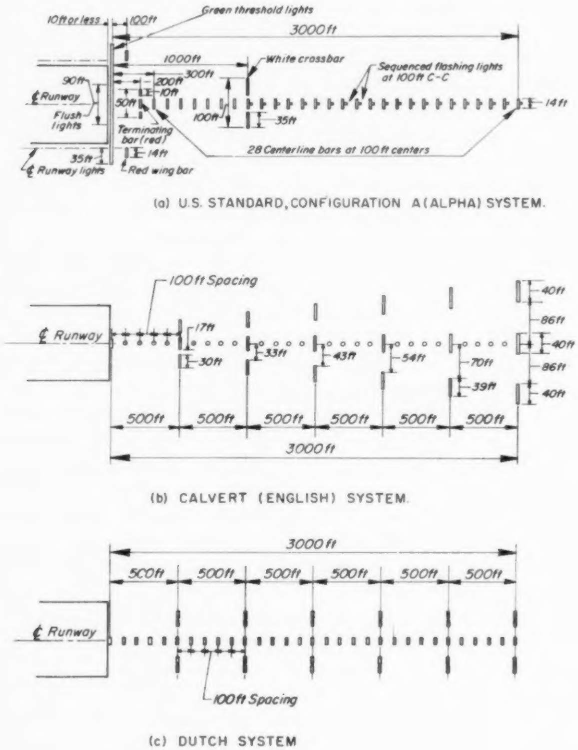


FIG. 6.—LAYOUT OF APPROACH LIGHTING SYSTEMS

long (Fig. 7). The candlepower of the end lights should, therefore, by very high, and the beam spread should be wide and deep. For example, if the visibility is defined as now suggested[4] by the NBS at 2,700 ft and if the slant range to the end light is 3,000 ft, the intensity of this light should be approximately 200,000 cp. To accommodate misalignment and variations in approach height, these outboard lights should have a horizontal beam spread of approximately 30° and vertical spread of 12°. These recommendations are considerably in excess of present practice.

As the aircraft approaches within the range of the threshold, the approach lights that are still in the field of view should be lower in intensity but wider in beam distribution. It may be noted that it the viewing distance of the last approach light is 500 ft while the visibility remains at 2,700 ft, the intensity of the light need be only approximately 50 cp. These data are taken from the NBS report[4] and are for nighttime conditions. The values are in general agreement with data taken by the writer and reported to the FAA.[6]

These recent studies indicate that the approach lights should be progressively increased in candlepower from the runway threshold to the outboard end and should be progressively decreased in horizontal and vertical beam spread from the runway threshold to the outboard end.

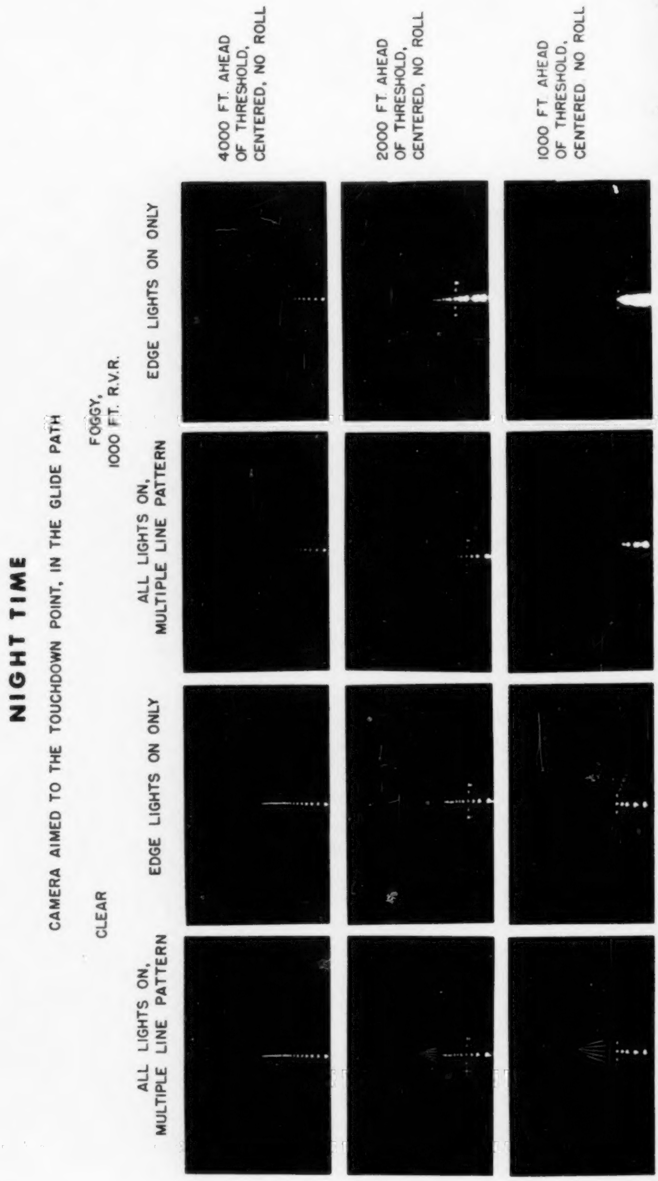
The distance from which the approach lights may be seen is greatly reduced when the visibility is low; so too is the time available for making corrections to the flight path. It has been found through experience that 3 sec is approximately the minimum time required for a pilot to perceive a visual aid and cause the aircraft to react. This 3-sec interval is a function of many variables which depend on the pilot and the aircraft, but it is a reasonable design criterion.

If a minimum of 3 sec is required for perception, corrective action, airplane response and checking the response, and if the aircraft has an assumed speed of 150 mph (220 fps) then the minimum visual range that could be permitted under IFR conditions would be 660 ft. The 660 ft should be along the ground, extending ahead of the nearest ground object that can be seen, so that the pilot will know where his aircraft is heading and what corrective action, if any, he should make. Fig. 4 shows the visual range, distance, and height relationships for a landing along a 2 ½ glide path.

The foregoing assumed conditions dictate the required length of the approach lighting system when the transition from the instrument flying to visual guidance is to be made at a height of approximately 200 ft. Using a cockpit cut-off angle of 15° below horizontal and assuming that the 600 ft to 700 ft of approach lights should be seen before the instrument-to-visual transition takes place, the approach lights must extend 3,000 ft ahead of the runway threshold. The slant range to the most distant light in view will vary from approximately 1,400 ft at 200 ft elevation to 850 ft at 50 ft. Thus it is evident that the outermost approach lights will be required to penetrate a greater distance in fog that the lights at the threshold of the runway, if the attenuation of the atmosphere is uniform in the region under consideration.

In good visibility conditions, approach lights may be a desirable supplement to a runway lighting system, but their use is not critical under these circumstances. In poor visibility conditions, the approach lights are mandatory, since they serve as the sole visual aid available at the start of the final phase of landing. These lights must provide proper guidance during the few seconds that it takes to travel from the approach area to the runway threshold. The lights must be designed for the most critical conditions of weather in which aircraft will be permitted to land. At present (1961) the weather minimums for landing at many airports are: (1) not less than a 200 ft ceiling, and (2) at least ½ mile visual range at airports equipped for full instrument landings.

Approach lighting has evolved gradually, mostly on an empirical basis. Over twenty different lighting configurations have been proposed and installed at various airports in the world. Even today there are approximately ten systems in operational use in different major airports. These chaotic conditions


NIGHT TIME
CAMERA AIMED TO THE TOUCHDOWN POINT, IN THE GLIDE PATH
CLEAR
FOGGY, 1000 FT. R.V.R.
ALL LIGHTS ON, MULTIPLE LINE PATTERN
EDGE LIGHTS ON ONLY
ALL LIGHTS ON, MULTIPLE LINE PATTERN
EDGE LIGHTS ON ONLY
4000 FT. AHEAD OF THRESHOLD, CENTERED, NO ROLL
2000 FT. AHEAD OF THRESHOLD, CENTERED, NO ROLL
1000 FT. AHEAD OF THRESHOLD, CENTERED NO ROLL

NEAR THRESHOLD, CENTERED, NO ROLL

NEAR THRESHOLD, CENTERED, 10° ROLL

NEAR THRESHOLD, 75 FT. TO THE LEFT OF THE CENTERLINE, NO ROLL

NEAR THRESHOLD, 75 FT. TO THE LEFT OF THE CENTERLINE, 10° ROLL

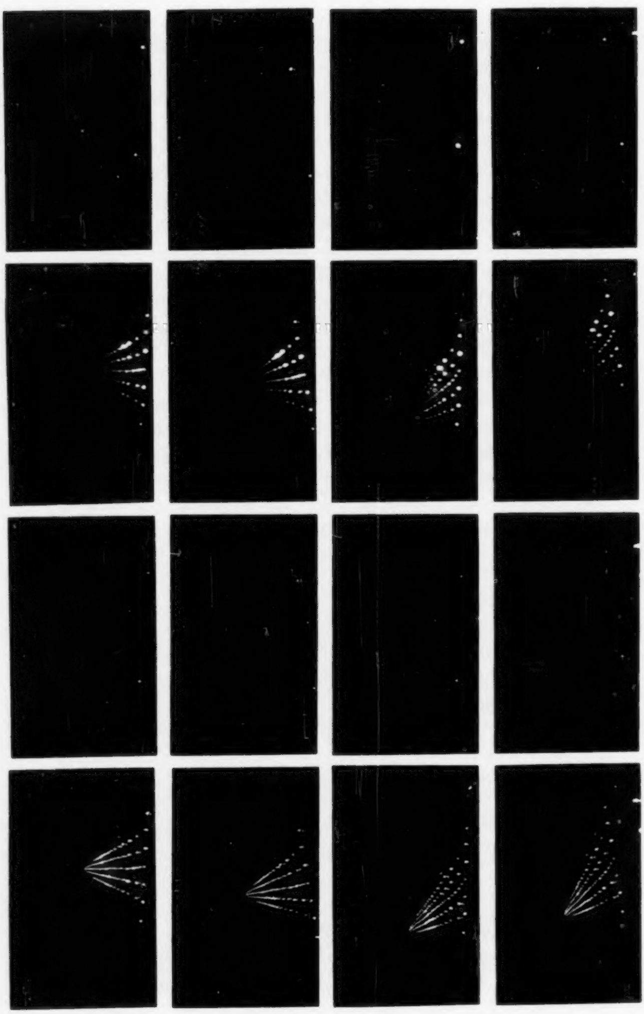


FIG. 7.—SCALE MODELS OF GUIDANCE SYSTEMS

should change rapidly, now that the FAA and USAF have agreed on a uniform pattern known as Configuration A or ALPA System, and the international associations are in the process of formulating an agreement. A plan view of the Standard System, Configuration A is shown in Fig. 6 and the full details are given in TSO-N24.[7]

Some airports, mostly military, require that the approach lights within 1,000 ft of the threshold be approximately flush with the graded surface. This specification has prevented the use of centerline lighting with a Configuration A pattern on these airports for a number of years, because suitable flush hardward was not available. The requirement can now be met by several different designs of equipment, so the USAF has agreed to the use of centerline approach lighting as a basic requirement for an approach lighting system.

Sequence flashing lights in the approach zone are also a relatively recent addition to the approach lighting system. The lights are located along the centerline of the approach lights and are arragned to flash consecutively to give the appearance of motion along the centerline. An extremely high intensity condenser discharge type of light has been developed and is now in use in some military and commercial airports. These lights develop as much as 30 million candlepower for a period of approximately 5 milliseconds. Pilot reports and opinion surveys show that these lights are effective as beacons to locate the runway in very poor visibility. Operation experience seems to indicate that the sequence flashed lights should only be used in very bad weather. They cause excessive glare in clear weather and do not add to the visual information provided by the steady-burning approach lights. There seems to be a difference of opinion about the advisability of using the flashing lights along the full length of the approach lights. Most observers, including the writer, favor stopping the flashing lights at the 1,000-ft bar. This suggestion is based on the argument that the lights are in the critical central field of view; they do not provide roll, height, or distance information; and the bright light interferes with the pilot's acuity and contrast snesitivity in the last critical phase of the landing.

THRESHOLD LIGHTING

During the last phase of the final approach for landing, the pilot must make a critical decision to either complete the landing or to execute a "missed approach" procedure and recover a flying attitude for the aircraft. For large military and commercial jet aircraft, the latter decision must be made when the aircraft is at least 1,000 ft to 1,500 ft from the threshold and is 50 ft to 75 ft high. The pilots of smaller aircraft can usually postpone their cedicion to a region nearer the touch-down point.

The threshold identification is a major element in determining the pilot's decision to land or not to land. The standard approach-light pattern now includes a terminating bar of red lights and two wing bars of red lights at the end of the approach lights, plus a solid row of green threshold lights extending across the end of the runway and beyond to the threshold wing bars 35 ft long on each side. The problem of the visibility of the threshold has been seriously and attentively considered, and this practical interim solution is available.[7] The ultimate solution has not been achieved, as is evidenced by the research and flight tests that are continuing at the National Aviation Facilities Experimental Center at Atlantic City, N. J. and other places.

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[7] TSO-N24a, Approach Lighting, FAA Tech. Standard Order.

The current research on threshold lights[4] indicates that, under clear weather conditions, it is desirable to have the lights readily visible from the base-leg turn (about 2 miles from the threshold on a straight-in approach). Under actual approach conditions, the minimum beam spread required is approximately 20°. Many of the lighting fixtures now in use as threshold lights do not have this required beam spread.

The transverse spacing is also being investigated by the FAA.[4] Data seem to indicate that, from a mile or more away, spacings of 2.5 ft to 5.0 ft are not distinguishable as separate sources, but that the effective intensity of the 2.5-ft spacing is approximately twice that of the 5.0-ft spacing, due to the additive effect of the closely spaced lights. Separation distances of 10 ft or more were not considered to be satisfactory. Calculations show that at 5,000 ft a 5-ft separation will subtend approximately 4 minutes of arc, whereas a 10-ft separation would develop about 8 minutes of arc. For bright point sources with a 4 minutes of arc separation, the flare of the lights will cause them to merge into an almost continuous line. An 8 minute of arc separation will not permit the lights to appear continuous. It has been concluded, therefore, that a 5 to 8 ft spacing distance will be recommended for the threshold lights.

The green filters used on the conventional incandescent sources add a further complication due to their absorptance; only about 20% to 40% of the clear light is transmitted. Therefore, to obtain adequate intensity for the threshold lights, higher regulator settings or higher wattage sources should be used, or a number of design parameters should be combined to bring the intensity of the threshold lights up to approximately the intensity of the approach lights when the aircraft is approximately 5,000 ft to 8,000 ft away. The vertical beam distribution should be carefully considered to avoid excessive glare at close positions. The foregoing suggests that the threshold lights should have a sharp vertical cut-off and a wide horizontal spread with the top of the beam aimed to intersect the glide slope at 5,000 ft. Further design work on threshold lighting fixtures to meet this need is suggested.

RUNWAY LIGHTING

After crossing the threshold of the runway at a safe height of 20 ft to 60 ft, the pilot must complete the touch-down and roll-out on the runway. This final pahse requires visual aids to make a successful flare, touch-down, and roll-out, no matter what the weather conditions may be. Even if fully automatic landings could be made, the pilot would need visual aids to monitor the system. For most jet thransport aircraft, the landing must be complete after the aircraft has proceeded to this stage in the approach. For all aircraft except experimental military models, the electronic aids for complete automatic landings are still several years away from practical application.

The runway visual aids should be designed to give the pilot all of the information that he needs to meet the requirements that have been discussed previously. But he no longer needs information to identify the runway nor directional guidance to locate the runway. He does need alignment, lateral displacement, roll, height, and distance information. This could come from the simplest kind of visual pattern that provides automatic registering of the information by his mental process. The interpretation of the data and his reflex actions must be so rapid that there is no conscious time interval needed to unscramble a maze of complex signals. In the daytime and in clear weath-

er the texture of the paved runway, the painted markings, and the surrounding ground provide the required data. At night and in poor visibility the texture and contrast data are not available, so lights are needed to provide the same information. The basic premise herein proposed is that the pattern of lights should yield the same basic visual data as the clear weather, daytime scene.

This general principle has been known and understood for many years and several techniques of implementing the design objective have evolved. At first, night landings were made by floodlighting a general area. Various types of lighting devices were used, including automobile headlights, arc lights, and searchlights. Boundary lights were added to mark the outline of the field and hazard lights were used for obstructions such as ditches, fences, etc. Gradually, preferred landing directions were developed and special lights were used to show these approach lines. The general floodlighting was then restricted to preferred landing directions, and runway edge lights were added along the landing strip. As experience developed, the runway edge lights were made more directional and higher in intensity, and the floodlighting was gradually abandoned, as were the boundary lights. We seem to be completing the cycle by going back to circling approach lights which are similar to the boundary lights, and to techniques of defining the touch-down zone which are not too much more different than those used in the floodlighting era.

The edge lighting system shown in Fig. 2 (b) is almost universally used, since it is approved, financed, and installed by the FAA. The lighting units are spaced on 200-ft centers along both sides of the entire runway. Breaks in the spacing may occur at intersections of runways and at exits to taxiways. The lateral spacing between the two lines is dependent on the runway width, and varies between 150 ft and 300 ft. The specific details of spacing and edge clearance to the side of the paving is available.[8] The standard color is white except on instrument runways, where aviation yellow is used on the first 2,000 ft to aid the pilot in judging distances and to provide distinctive identification for instrument runways. Edge lights are primarily signal lights intended for direct observation and are not designed for the purpose of illuminating the runway.

Runway edge lights are classified on the basis of their candlepower as low (1,000 cp maximum, 30 to 50 watts), medium (1,000 to 10,000 cp maximum, 30 to 50 watts), and high (10,000 to 200,000 cp, 50 to 500 watts). They are also classified on the basis of their physical height as:

Low-profile.—Lights not over 1 in. above the adjoining pavement level. For special purposes such as on military airports for high performance jet aircraft, the military specifications now require that the lights shall not project more than 1/8 in. above the surface of the pavement. Also for regions requiring snow plowing, it has been found that heights of 7/16 in. or less are desirable.

Flush.—Lights not over 1 3/4 in. above the adjoining pavement level. The sides are generally sloped to permit roll-over by aircraft without damage to either the light or the aircraft and to allow snow plowing at nominal speed of the plow.

Semi-Flush.—Lights not over 3 1/2 in. above the adjoining pavement level.

Elevated.—Lights not over 30 in. above the adjoining pavement and mounted on frangible supports.

High-intensity runway edge lights are considered by the FAA to be a part of the approach lighting system and therefore they should be planned and budg-

eted with the approach and threshold lights. The brightness of the edge lights should be controlled in the same manner as the approach lights, using the prescribed five steps.[7,8]

"BLACK HOLE" EFFECT

The system of lighting described previously causes a visual phenomenon known to pilots as the "black hole." As the aircraft proceeds over the approach lights, the pilot is first looking along the centerline at the relatively bright approach light sources and the two rows of edge lights that are not far from his central field of vision. As the aircraft passes over the runway threshold, the pilot continues to look along the centerline, but it is suddenly very dark because there are no more centerline lights and the change in perspective angle has caused the edge lights to move far to each side in his peripheral vision. The result is that the central area appears excessively dark. He is virtually flying blind except for the peripheral reference information. Attempts to eliminate the black hole by increasing the intensity of the edge lights have been ineffective and actually cause the hole to be blacker, as would be expected from our knowledge of his state of adaptation.

In order to relieve the "black hole" effect, several designs of low-profile lighting units have been developed in recent years that can be installed directly in the runway pavement. The idea is to develop a visual pattern in the central field of view on the runway in the touch-down zone within the boundaries of the runway edge lights. Several patterns have been proposed and some have been installed and flight tested.

The "Narrow Gage" pattern was the first to be used. This system consists of two parallel rows of lights embedded in the runway on a 60 ft to 75 ft gage (30 ft to 37 ½ ft each side of the centerline) with 100 ft to 200 ft between units along each row extending for 3,000 ft along the runway beginning at the threshold. In the field tests conducted in the United States and abroad, the lighting elements used in the units were of the medium or high intensity type. The brightness of the system could be controlled in five steps, using conventional regulators. The tests so far conducted by the USAF at March AFB, Andrews AFB, Dow AFB and the FAA at Idlewild Airport at New York and at NAFEC at Atlantic City, N. J. seem, to give support to the idea that lighting on the runway within the "black hole" is highly desirable. But the best pattern for the touch-down lights has not yet been resolved.

Other lighting units being considered to develop the lineal patterns of the runway are "inset lights" of the very low-profile type (less than ½ in. projection above the adjacent surface) and are rated low-intensity 3 cp to 70 cp). However, the brightness of each point source is very high, and the units are designed for direct viewing of the incandescent filament. The principle involved is that a large number of small, high-brightness sources are viewed in a longitudinal array and are spaced so closely that virtually a continuous high-brightness line is developed. This causes an effective build-up in the intensity of each source due to the ladder effect of the closely spaced units. This is the same phenomenon that was reported ay the NBS and FAA in the discussion of the threshold lighting.[4] The principle is gaining acceptance and may become a recognized technique in the near future. The power used for the low-

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[8] TSO-N1C, Runway Lighting, FAA Tech. Standard Order.

profile, button lights in the trial installations varies from 3 watts to 45 watts. Experimental units using 100 watt to 200 watt sources are being considered. The writer is confident that these higher wattages are not required to accomplish the purpose for which the touch-down zone lights are intended, namely, guidance from approximately 1,000 ft ahead of threshold to touch-down and on through the roll-out to the taxiway.

Discussion continues as to whether centerline guidance lights should be installed between and beyond the narrow gage lights, whether additional lines of lights would be helpful, whether transverse bars should be included in the pattern, what the spacing and intensity should be and what brightness controls should be provided. Development work is continuing on alternate designs of the lighting units and the patterns of lights. The five-line pattern referred to priviously has been set up on flight simulators and in models in fog chambers. In this writer's opinion, it seems to show great promise.

Most of the visual problems of the pilot during the landing, including the touch-down zone, have been considered herein. But there are still unanswered questions regarding landing and take-off operations in very bad weather with much lower visibilities than are now permitted. On the basis of unpublished research now in progress, it is the writer's opinion that it should be possible to safely land and take off aircraft in weather with a zero ceiling and a runway visual range of as low as 1,000 ft. The basis for this statement is presented subsequently:

In the region of the approach zone in which the downward cut-off angle of the cockpit does not exclude the end of the approach lights, the termination or the threshold lights, the lighting problems are now understood and can be solved to provide adequate pilot guidance information even in 1,000 ft RVR weather. Near the threshold region where the cockpit cut-off does exclude the threshold lights, (150 ft to 200 ft from the threshold) the only visual elements in the field of view in 1,000 ft RVR weather will be a few (perhaps 3 or 4) edge lights on each side of the runway. These lights may be supplemented by some very low-contrast surface detail objects in the near foreground, but, in general, the scene is considered by pilots to be woefully inadequate. But since the aircraft is then only about 50 ft high and the required slant range is approximately 850 ft, a suitable brightness pattern can be built up on the runway that can furnish all of the necessary visual information. The drawings in Figs. 2 and 3 and the photographs in Fig. 7 demonstrate the argument. A typical runway is shown in Figs. 2 and 3 from an aircraft position on the glide path just prior to crossing the threshold, but after the cockpit cut-off has blocked off the threshold of the runway. Note that the daytime scene in clear weather shows a very distinct pattern with a large amount of visual information. In the nighttime scene in clear weather the basic pattern is reduced to a bare minimum of two edge lines plus some horizon information. The nighttime clear-weather scene can be improved to make it more like the daytime scene by adding a centerline and/or two narrow gage lines. The total visual information can be further enhanced by using more lines, such as in the five-line pattern. The clear-weather situation is not critical, however, and even the bare edge-line pattern is quite pracitical, as we know from the present operating experience.

The real test of pattern, spacing, intensity, beam distribution and adequacy comes in the very low visibility situations. Fig. 3 is an attempt to show what happens to the clear-weather scenes when the RVR is reduced to about 1,000 ft.

The visual impressions are quite conclusive and show that a centerline plus additional lines provide much better guidance than edge lights alone. Since Figs. 3 (a), (b), (c), and (d) are only drawings, one might have reservations about their fidelity. To supplement the drawings, a series of photographs taken in the University of California Fog Chamber is shown in Fig. 7.

The photographs of Fig. 7 were made using scale models with the distances and light intensities scaled down to represent the runway lights at approximately full brightness, except that the runway edge lights are shown at the equivalent intensity of about Step 3 in service. The contrast between the minimum "edge lights only" pattern and the five-line pattern is most striking, especially under the heavy fog conditions. One can observe that the various approach directions and roll attitudes of the aircraft are readily interpreted when adequate ground reference data are presented. It is evident that such information can be transferred to the pilot even in very bad-visibility weather, provided that an adequate lighting pattern is developed.

The extension of the concept of lineal guidance to roll-out and taxiway operational installation is now in use at Idelwild Airport in New York and a second is in use at the San Francisco International Airport. This discussion will not review the taxiway lighting problems in detail.[9,10] The subject is mentioned because it is very important and has been a part of the aviation ground lighting research conducted by the writer.[6,11,12,13]

The airport lighting problems have been many and varied. It has taken a long time to arrive at what seems to be at least a partial answer to "all-weather landings and take-off." Some unanswered questions still remain, but it does seem that the application of present knowledge of both electronic and visual aids to airports and aircraft could permit reliable operation of commercial and military aircraft for almost all weather conditions.

DISCUSSION

R. F. GATES.[14]—Mr. Finch's low profile lighting fixture prototype was simply constructed, glued on the runway, and used low wattage European-type automobile lamps (Fig. 8).

Finch accurately predicted that the FAA would not leave his product in its simple, original form. The following illustrations show the evolution of this

[9] TSO-N3a, Taxiway Lighting, FAA Tech. Standard Order.

[10] TSO-N23, Taxi Sign System, FAA Tech. Standard Order.

[11] "Exit Taxiway Location and Design," by Robert Horonjeff, et al., Report to the Airways Modernization Board, Contract No. AMB*4, August, 1958.

[12] Letter Report to Julian Bardoff, Senior Civ. Engr., Utilities Engrg. Bur., San Francisco, Calif., by Robert Horonjeff and Dan M. Finch, December 22, 1960, covering installation of centerline taxiway lights at San Francisco Internatl. Airport.

[13] "Airport Lighting Studies," by Dan M. Finch, Special Report VCB-Eng. 6439, December 27, 1960, for Oakland Internatl. Airport. Rendered to the Port of Oakland, Oakland, Calif.

[14] Federal Aviation Agency, Bur. of Research and Development, Natl. Aviation Facilities Experimental Center, Atlantic City, N. J.

fixture since the University of California installation on the runway centerline at San Francisco airport. Fig. 9, the first fixture developed under a Bureau of Research and Development (BRD) contract, was 6 in. in diameter, protruded 7/16 in. above the pavement, used an exposed quartz-type lamp, and was recessed 1 in. in the pavement instead of being glued to the surface. This

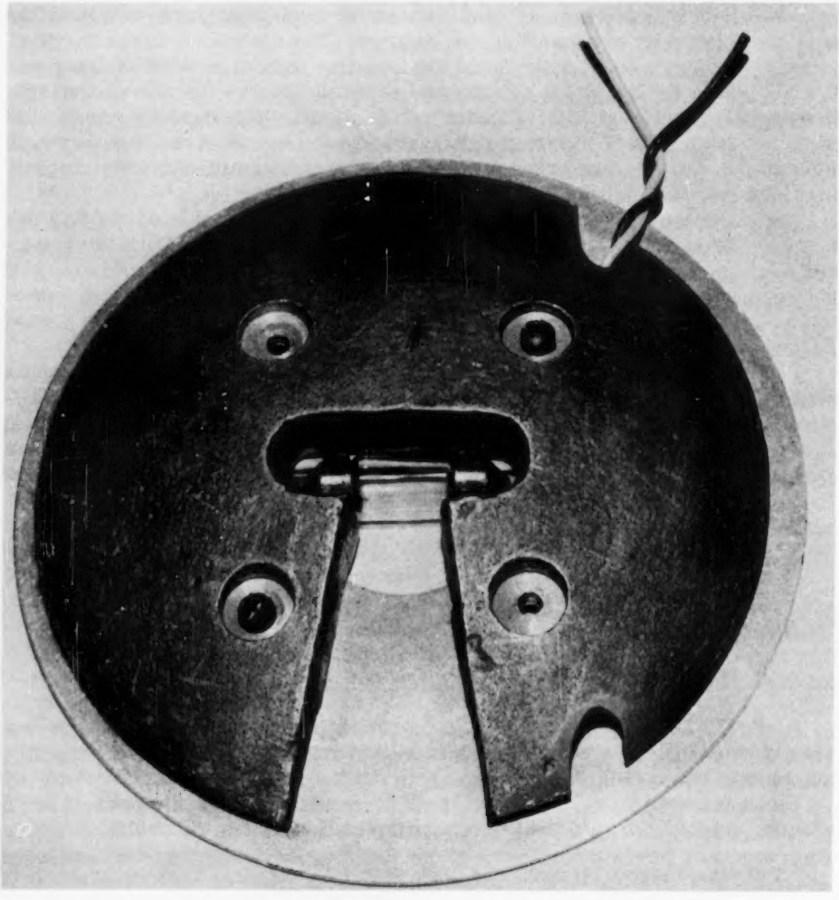


FIG. 8.—FINCH'S PROTOTYPE FIXTURE

unit was fractured by snow plow blades and the height resulted in noticeable roughness in the airframe of aircraft. Consequently, the next step was to lower the height to $\frac{1}{4}$ in. above the surface (Fig. 10), and lower the slope of the fixture by using an 8-in. diameter instead of 6 in.

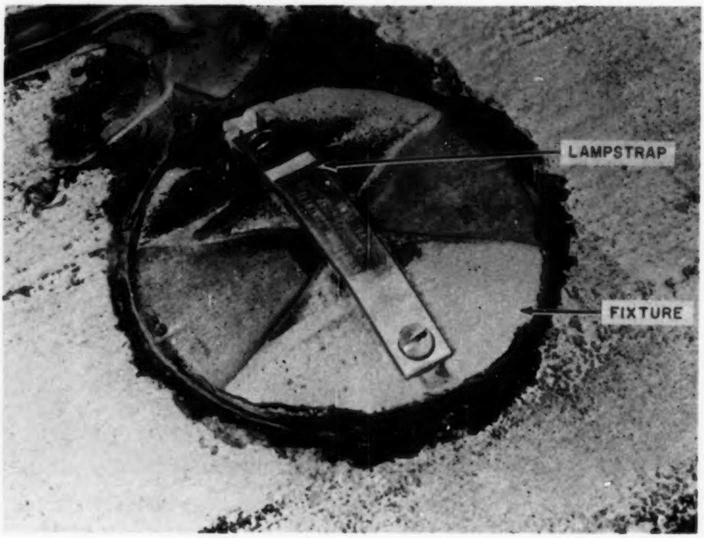
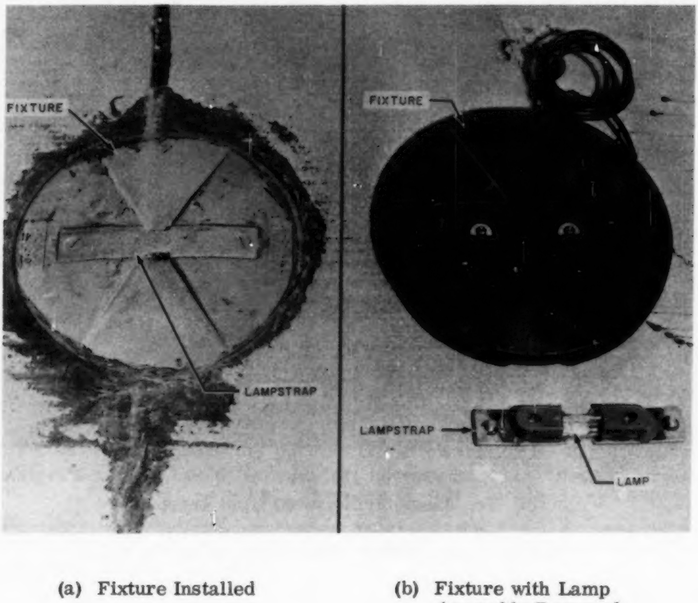


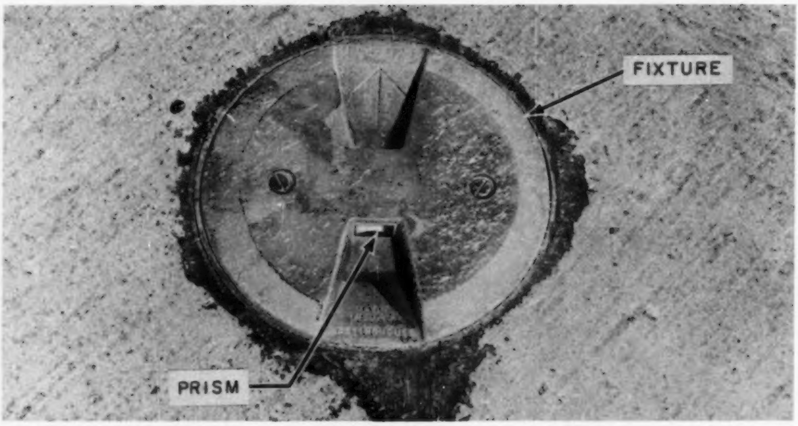
FIG. 9.—STRUCTURAL 6-IN. INSET TYPE OPEN FIXTURE



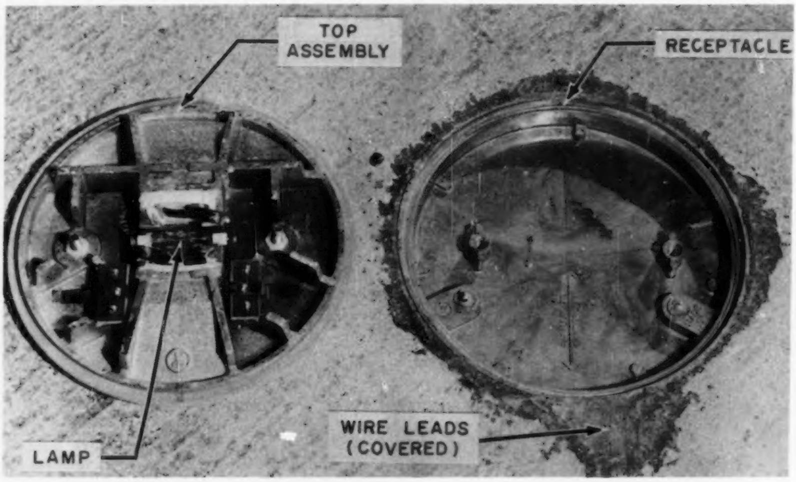
(a) Fixture Installed

(b) Fixture with Lamp Assembly Removed

FIG. 10.—8-IN. INSET TYPE OPEN FIXTURE



(a) Fixture in Runway



(b) Top Assembly Removed from Receptacle

FIG. 11.—8-IN. INSET TYPE ENCLOSED FIXTURE

The open-quartz lamp intensities are reduced rapidly due to the baking of foreign matter on the hot glass envelope. The quartz lamp has been broken in such large numbers that the trend is now toward the enclosed-type fixture (Fig. 11). The 85 cp of the 45-watt open-type fixture does not provide the required contrast for lighting patterns in daytime high-brightness fogs, so lenses have been utilized in the enclosed fixtures to concentrate the light and produce 500-1,000 cp in the main beam.

Some of the electronic landing aids begin to loss accuracy at heights of 150 ft to 250 ft above the ground, but localizer and glide path improvements and other developement effort should improve these conditions soon. The directional localizer has been found extremely accurate at the National Aviation Facilities Experimental Center (NAFEC), and a flush-mounted glide path antenna soon will be located in the runway which, it is hoped, will provide a continuous straight path to the runway surface. These improvements in ILS, plus the research and development efforts on coupled approaches on such systems as REGAL, BLEU, AN/GSN-5, and AN/APN-114, should result in the eventual landing of aircraft with passengers by electronic means. Although considerable improvements are being made in electronic landing systems, no inference is intended that Finch's view on the future requirements for visual aids is incorrect. It seems logical that both visual and electronic aids need to be improved to justify a decrease in operating minimums.

A promising touchdown lighting system tested at NAFEC was called a 3-2-1 system—a title that indicates the nature of the distance coding of the lighting pattern. Finch also has proposed a system incorporating distance coding. The fundamental differences between the two systems will be discussed subsequently, but it is noted at this time that both proposals include distance coding. Distance coding of touchdown systems also is supported by the IATA Flight Technical Group.[15] and the ICAO Visual Aids Panel.[16]

Fig. 12 shows how ten zones of distance information can be supplied for the pilot, from the beginning of the approach light system to the far end of the runway in use, by providing bidirectional fixtures in the second and third thousand feet of the 3-2-1 system. The assumption is made that touchdown lighting is installed at both ends of a runway and a mid-point lighting pattern of diamond shape also is available. The mid-point pattern has not been installed nor tested, but discussions with operations personnel indicate some such type of marking and lightin is desirable.

The 3-2-1 system (Fig. 13) consists of three light barrettes located symmetrically about a bidirectional-lighted centerline on a 60-ft gauge spaced 100 ft longitudinally in the first 1,000 ft (Fig. 14), followed by two rows of lights located symmetrically about the centerline on a 60-ft gauge spaced 25 ft apart longitudinally in the second 1,000 ft, and a single row of lights on each side of the centerline on a 60-ft gauge with lights spaced 25 ft apart longitudinally in the third 1,000 ft. The lights also are spaced at 25-ft intervals along the entire runway centerline. (Note the perspective views of these Figs. 13 and 14, since an impression of the difference in horizontal plane definition can be gained.)

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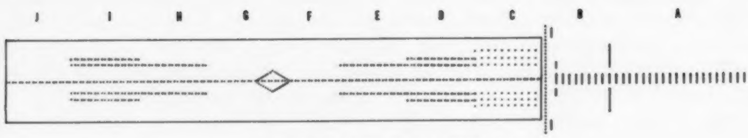
15 "Report of Flight Technical Group, Tenth Meeting," by IATA Flight Tech. Group, Atlantic City, N. J., October 4-7, 1960.

16 "Exchange of Views on the Principles Applicable to the Design of a Complete Lighting and Marking System," Visual Aids Panel Meeting, I. C. A. O., Montreal, Canada, November 16, 1960.



THE FOLLOWING DISTANCE CHECKS ARE AVAILABLE DURING APPROACH AND LANDING

A - APPROACH LIGHT (OUTER ZONE)

B - APPROACH LIGHT (INNER ZONE)

C - TRANSITION ZONE

D - TOUCHDOWN ZONE - FIRST 1,000 FEET

E - TOUCHDOWN ZONE - SECOND 1,000 FEET

F - ROLL OUT TO ONE-HALF RUNWAY LENGTH

G - ROLL OUT BETWEEN MID POINT AND 3,000 FEET REMAINING

H - 3,000 FOOT ZONE (FROM RUNWAY END)

I - 2,000 FOOT ZONE (FROM RUNWAY END)

J - FINAL 1,000 FOOT ZONE

NOTE - ON TAKEOFF, CENTERLINE PROVIDES DIRECTIONAL GUIDANCE AND ZONES H AND I PROVIDE ADDITIONAL DISTANCE-TO-GO INFORMATION PLUS ATTITUDE GUIDANCE DURING CLIMB OUT AFTER BREAKING GROUND

FIG. 12.—DISTANCE INFORMATION OF 3-2-1 SYSTEM

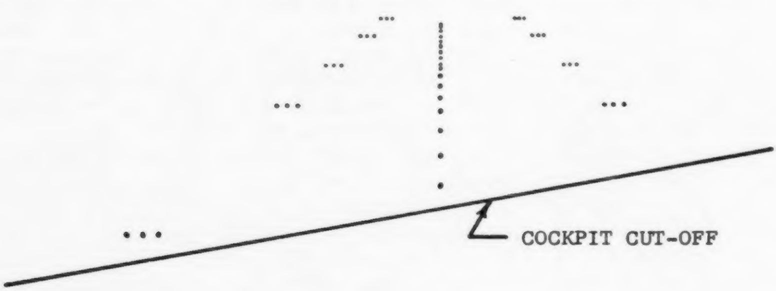


FIG. 13.—PERSPECTIVE VIEW—TRANSITION ZONE 500-FEET RVR

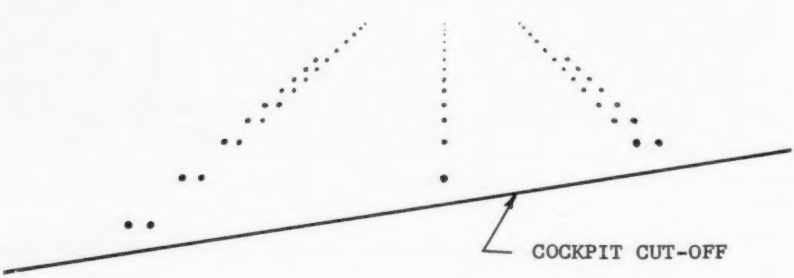


FIG. 14.—PERSPECTIVE VIEW 3-2-1 SYSTEM 500-FEET RVR

The fundamental differnece between Finch's proposal and the 3-2-1 pattern concerns the location of the touchdown zone. Finch stated that the actual touchdown point may fall within a range of 0 to 3,000 ft from the runway threshold (Fig. 15). Fig. 15 shows what happens at zero point due to erosion of the soil under jet blast - a vertical wall of concrete exists convenient for "wiping off" undercarriages of aircraft. In 1960 at NAFEC, a C-118 hit a bank of snow at zero point. It lost its main gear and left wing which, fortunately, separated from the fuselage and burned alone behind the balance of the wreckage; the list of such accidents is long and has cost many millions of dollars.

The first 1,000-ft zone of the 3-2-1 pattern is not considered to be touchdown lighting, although it can be used as such by pilots who wish to exercise their "prerogative." This zone consists of lights with intensities of about one-half of those used in the approach light zone (15,000) (Fig. 16). A bold pattern change is provided which serves to identify the beginning of the runway, but the primary purpose of these lights is to provide transition guidance from the approach lights to the touchdown zone which commences 1,000 ft from the runway threshold. In a sense, the first 1,000-ft zone is a continuation of the ap-

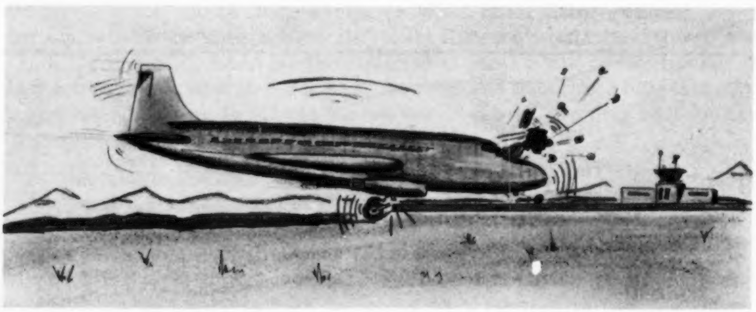


FIG. 15.—TOUCHDOWN ZONE COMMENCES AT THRESHOLD

proach light system and an aiming point is created by pattern change at the 1,000-ft point.

The second and third 1,000-ft zones provide sensitive definition of the horizontal plane, improved directional guidance, additional distance coding (Fig. 17) and roll guidance. Instead of the high-intensity "brute force technique, guidance is obtained by increasing the rate of flow of visual cues. There is very little loss of runway visual range when making transition from the higher intensities, since the effective candlepower of the lower intensities is increased due to the augmentation effect of the closely spaced fixtures. The increased rate of visual cues appears to compensate for any loss in runway visual range. A most significant advantage of the longitudinal lines of low-intensity lighting is the elimination of glare. These lights lose the augmentation effect as they flow toward the eye and, consequently, appear to maintain uniform brightness. This feature of the system accomomdates vision, enabling the pilot to proceed out of the touchdown zone along the one centerline row of lights for roll-out with a minimum of dazzle effect.

It is interesting to note that as early as January, 1947, Mr. Calvert of England prepared a report[17] which stated that, in his opinion, longitudinal lines of lights in a "contact mat" were preferable (to transverse bars) because of the accuracy of the indications obtained at low heights.

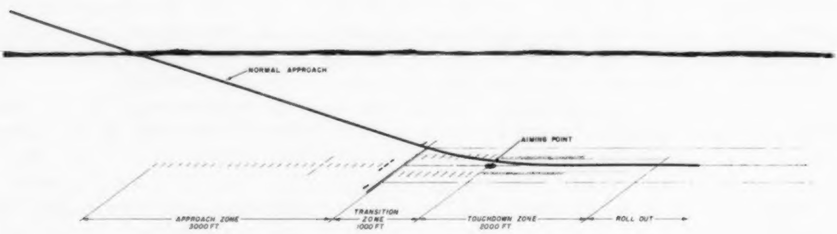


FIG. 16.—NORMAL APPROACH—3-2-1 SYSTEM

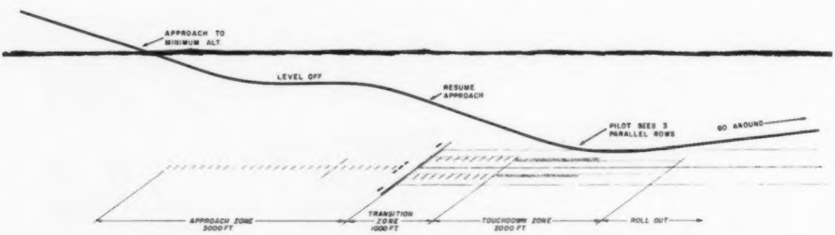


FIG. 17.—OVERSHOOT—3-2-1 SYSTEM

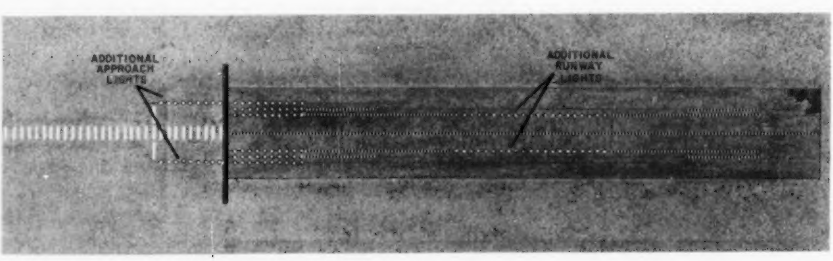


FIG. 18.—POSSIBLE IMPROVEMENTS TO LIGHTING SYSTEM

In addition to operating the approaching lights in the outer zone at higher intensities, as stated by Finch and as reported by Charles Douglas,[18] the following two pattern changes might improve the lighting system (Fig. 18).

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17 "Visual Approach and Landing Aids for Aircraft, Fundamental Problems Analysed by Means of Perspective Diagrams," by E. S. Calvert, Preliminary Report, Report No. EL 1414, January, 1947.

18 "Development of Visual Landing Aids for Jet Aircraft," Report No. 6862, Final Report, Natl. Bur. of Standards, June, 1960.

1. Single row of high intensity lights could be added commencing at the 1,000-ft bar of the approach light system, symmetrically located on each side of the centerline on an 80-ft gauge. These lights would be spaced at 100-ft longitudinal intervals between the 1,000-ft bar and the runway threshold. Such longitudinal arrays of lights should:

a. Serve to identify the inner 1,000-ft zone of the approach light system since the 1,000-ft bar may not be seen in low visibilities.

b. Serve as a lateral deviation gauge for go - no go.

c. Provide additional roll guidance where some maneuvering or drift correction is required at low heights.

2. A second pattern change which may prove useful would be the continuation of the inset fixtures beyond the touchdown zone symmetrically located about the runway centerline on the same 60-ft gauge as the touchdown lighting but increasing the spacing to an interval 100-200 ft which would not be mistaken for the touchdown zone or the runway centerline. This would serve to extend the directional and lateral deviation visual guidance for the rollout and take-off operations. It is believed that with these additonal longitudinal lines, runway lights would serve little useful purpose other than outlining the runway for operations in snow where the inset fixtures would be snow-covered. Edge lighting probably could be discontinued if snow could be eliminated. High persistance phosphorescent-type markers might be substituted for this old reliable runway edge light to soothe the nerves of pilots who may be reluctant to part with such an old friend.

Other changes in the approach zone proposed by the USAF Dow Field Report[19] concern the elimination of the red wing bars and the substitution of another bar in the centerline. This may prove to be an improvement since the narrow gauge runway lighting serves as a strong threshold signal.

Our objective is to fly all weather with no compromise in safety of operations. Pilot training on visual simulators that reproduce the real environment should prove very helpful. Adequate pilot training coupled with improved electronic and visual aids should enable the aviation industry to obtain finally all-weather operations.

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19 "Test of an Integral Visual Approach and Landing Aids System," by Roy L. Strong, Category 111, 8th Air Force, SAC, USAF, June, 1959.

Journal of the

AIR TRANSPORT DIVISION

Proceedings of the American Society of Civil Engineers

SUMMARY OF PRESTRESSED CONCRETE PAVEMENT PRACTICES

By F. M. Mellinger,[1] F. ASCE

SYNOPSIS

Experimental work and actual construction of prestressed concrete airfield pavements has progressed on a limited scale since about 1946. This paper, by means of references, summarizes the development of design criteria for such pavements and reviews the types of construction used for prestressed concrete runway and taxiway pavements. It describes several investigational model programs, the construction of some of the major prestressed airfield pavements, and the possible advantages and limitations of several construction methods.

INTRODUCTION

Before a rational method of design for any type of structure can be postulated, the mode of failure must be visualized and the conditions leading to failure must be defined. Insight into the nature of failure may be gained from experimental work with models and with full-scale structures. Correlation of the results of such experimentation with applicable theory and analytical studies may then lead to a design method that, although not entirely satisfactory in its early stages, may be modified in the light of subsequent experience. Design methods for plain concrete airfield pavement have been formulated in this manner, and considerable refinement in both the design and construction

Note.—Discussion open until January 1, 1962. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Air Transport Division, Proceedings of the American Society of Civil Engineers, Vol. 87, No. AT 2, August, 1961.

[1] Dir., Ohio River Div. Labs., U. S. Army Corps of Engrs., Cincinnati, Ohio.

methods has been made over the past ten years to meet the exacting requirements of modern day military and commercial jet aircraft. The search for a rational design method for prestressed concrete pavement, has been under way in Europe since about 1944 and in the United States since about 1952.

Only a few major prestressed concrete airfield pavements have been built and placed in operation over the past six years (as of 1961). These are mainly in Europe, where at least four or five airfields have full length prestressed concrete taxiways, or runways, or both and, in some cases, prestressed aprons. These European pavements were preceded by a number of full-scale pavement slabs of limited area that were loaded experimentally to provide design information. The building of these experimental slabs also afforded experience with construction methods. At the present time (1961) there are no major prestressed concrete airfield pavements in the United States. However, a considerable amount of experimental work has been done with the construction of full-scale prestressed concrete pavements of limited area. Three such pavements of limited area have been built into a portion of a taxiway at three airfields in the United States.

Early analytical studies[2] started with the concept that the only function of the prestress in a concrete pavement was to increase the flexural strength of the concrete by the amount of the prestress. This concept was studied by the well known Westergaard analysis[3] currently used for the design of plain concrete pavements. It was assumed that the pavement would fail when the first crack occurred in the bottom of the pavement due to positive moment from the applied load. Naturally this did not provide much advantage for prestressing from an economical or practical standpoint. It was not until 1945 and 1946 that small experimental prestressed test slabs were cast at Orly Airport near Paris, France, and tested by static load tests. It was found that these slabs had a considerably greater load-carrying capacity than was indicated by computations based on increasing the flexural strength by the amount of the prestress and by assuming failure when the first crack due to positive moment occurred under the load. These tests and later ones led to the following concept of failure.

As successive increments of load are applied, the slab deforms elastically as indicated by the Westergaard analysis to the point at which the stress due to the maximum moment beneath the loaded area exceeds the sum of the applied prestress and flexural strength of the concrete. At this point a crack under the load in the bottom of the slab forms a plastic hinge.

With the formation of the plastic hinge under the loaded area, the moments in the slab are redistributed so that with additional increments of load there is no further increase in positive moment, but a substantial increase in radial moment some distance away from the loaded area.

This is the basis for the analytical assumption that tensile cracking occurs in the top surface of the slab when the maximum negative radial moment is equal in magnitude to the positive moment which produced the initial cracking in the bottom surface of the slab. The tensile cracking in the top surface of the slab forms visible circumferential cracks. When this condition is reached, failure is considered to occur.

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2 "Prestressed Concrete Runways; History, Practice, and Theory," by A. J. Harris, Proceedings, ICE, London, January, 1957.

3 "New Formulas for Stresses in Concrete Pavements of Airfields," by H. M. Westergaard, Transactions, ASCE, Vol. 3, 113, 1947.

When the loading is increased beyond this point, vertical shear failure occurs and the load punches through the slab.

An excellent discussion of this action is available.[4] Figs. 1 and 2 present some results of small-scale studies of prestressed plaster model slabs supported on a rubber subgrade. More complete details of these model studies are given elsewhere.[5]

Fig. 1 shows the progression of deflection of a model pavement slab as the load is increased in increments, first producing an initial crack due to positive moment, then cracking due to negative moment and finally failure due to vertical shear. This action is similar to that observed for full-scale static loading tests on prestressed concrete slabs. Fig. 2 shows a plot of the increase

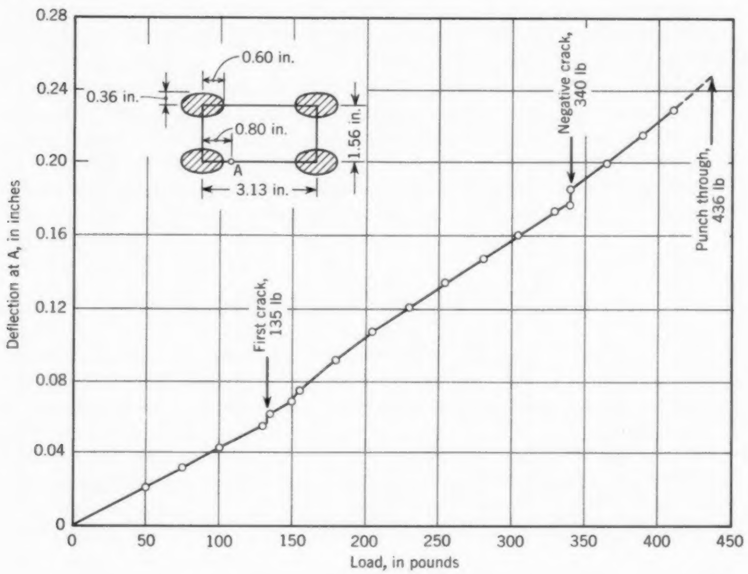

FIG. 1.—DEFLECTION OF PRESTRESSED MODEL SLAB LOADED TO FAILURE; 201 PSI PRESTRESS, 0.199 IN. THICK, TWIN-TANDEM LOADING

in stress due to negative radial moment as the loading on the model slab carries through the elastic state and the slab approaches failure by tensile cracking in the top surface.

In Europe, except for the observation of the performance of existing prestressed concrete pavements, experimental work has consisted of static load

4 "Prestressed Concrete Pavements," by E. C. Molke, Proceedings, ASCE, Vol. 85, No. AT3, July, 1959.

5 "Model Studies of Prestressed Rigid Pavements for Airfields," by P. F. Carlton and Ruth M. Behrmann, Highway Research Bd., Bulletin 179, 1958.

tests on full-scale prestressed concrete slabs. Repetitive static loading has also been applied. Methods of analysis and design have been based on the results of these tests. Excellent examples of such work have been presented.[6,7,8]

In the United States, experimental studies of prestressed concrete airfield pavements have been conducted chiefly by the United States Navy, Bureau of Yards and Docks and by the United States Army Corps of Engineers for the United States Air Force. This work as well as that of others in this country has been summarized.[9]

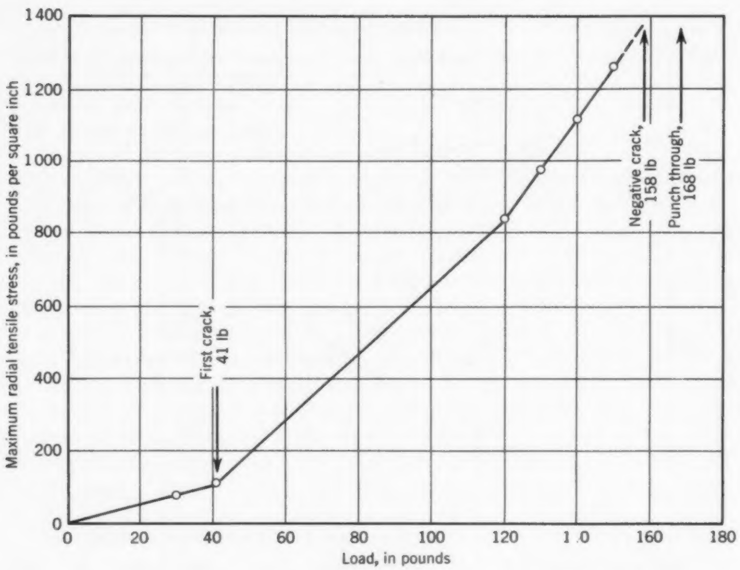

FIG. 2.—MAXIMUM RADIAL TENSILE STRESS IN TOP SURFACE OF A PRESTRESSED MODEL SLAB; 204 PSI PRESTRESS, 0.196 IN. THICK, 0.50 IN. RADIUS LOADING

Experience of the Corps of Engineers in establishing design procedures for plain concrete pavements has shown that full-scale static loading tests of

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6 "Experimental Theoretical Study of a Prestressed Slab on an Elastic Support Beyond the Limits of Elasticity," by F. Levi, Annales de l'Institut Technique du Batiment et des Travaux Publics, June, 1953.

7 "Design of Prestressed Concrete Runways," by P. D. Cot and E. Becker, Revue Générale des Routes et des Aérodromes, No. 292, May, 1956.

8 "Prestressed Concrete Pavements—A Review of European Practice," by D. Vandepitte, Proceedings, Prestressed Concrete Inst., Vol. 6, No. 1, March, 1961.

9 "Experience with Prestressed Concrete Airfield Pavements in the United States," by C. F. Renz and P. L. Melville, Proceedings, Prestressed Concrete Inst., Vol. 6, No. 1, March, 1961.

pavement slabs are of limited value because they cannot simulate the effect of repeated traffic loading.[10] The effect of repeated traffic load must be known for the establishment of design criteria for pavement built for a specified aircraft loading, type, and frequency of operation. Although the installation of operational prestressed pavements is quite limited in this country, the experimental work conducted by the Corps of Engineers over the past six years has been extensive and has sought to provide information about the behavior of pavement subjected to repetitive loading.

Full-scale traffic loading tests using twin-wheel gear loadings ranging from 60,000 lb to 100,000 lb have been made. These tests were conducted on a 4-in. thick prestressed overlay pavement over a 6-in. thick plain concrete base pavement.[11] In addition, full-scale traffic tests have been completed on a 9-in. thick prestressed concrete test pavement 500 ft long by 50 ft wide. These pavements were trafficked with a twin-tandem four-wheel gear arrangement with loads ranging from 200,000 lb to 265,000 lb. A description and principal results of these tests are available.[12] More recently the Corps of Engineers has built and is operating a small-scale traffic loading device by which traffic or repetitive wheel loading can be applied to about 1/10 scale models of prestressed pavement slabs on a soil subgrade. Good correlation has been obtained between these tests and full-scale tests. Extrapolation of results from the traffic tests to design parameters is accomplished by tests of small-scale plaster models of prestressed slabs.[5] This small-scale model is used as an analog computer.

PRESTRESSED PAVEMENT MODEL STUDIES

Two types of prestressed pavement models will be discussed. The first type is a small plaster (Hydrocal—a gypsum compound) slab 17 in. square and 0.2 in. thick supported on a 12-in. thick layer of natural rubber 24 in. square. Single strands of music wire positioned at mid-depth provide a rectangular grid of tendons for prestressing the slabs. Generally an 0.02-in diameter wire spaced on 0.6 in. centers is used. The models are tested by applying loads through circular or elliptical footprint areas dimensionally scaled to aircraft gear configurations. Deflection and strain measurements are made under various increments of loading.[5,12]

This type of model has proven to be a very versatile analytical tool. It is essentially an analog computer since it checks theoretical solutions closely where boundary conditions are within the scope of the theory. In the case of prestressed pavements, it is used to develop constants that greatly simplify the computation of the maximum radial moment causing cracking in the top surface of the slab. The model has also been used to obtain some idea of the benefits in load-carrying capacity resulting from an increase in the amount of effective prestress in a pavement. The results of such a study are shown in Fig. 3. Fig. 3 gives values for a series of tests made on model slabs with

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[10] "Development of Rigid Pavement Design Criteria for Military Airfields," by J. P. Sale and R. L. Hutchinson, Proceedings, ASCE, Vol. 85, No. AT3, July, 1959.

[11] "Prestressed Concrete Airfield Pavements," by F. M. Mellinger, Proceedings, World Conf. on Prestressed Concrete, San Francisco, Calif., July, 1957.

[12] "Development of a Procedure for the Design of Prestressed Airfield Pavements," by P. F. Carlton, 39th Annual Meeting of the Highway Research Bd., Jan., 1961.

effective prestress ranging from 0 to approximately 500 psi. The lower curve indicates the load at which the first crack occurs beneath the loaded area, due to the maximum positive moment, for various levels of effective prestress, while the upper solid curve shows loads at which the surface crack forms due to the maximum negative radial moment. This moment is approximately equal to the maximum positive moment. These curves indicate the increase in load-carrying capacity of prestressed pavement above that obtained if failure were defined by the first crack produced by positive moment. The negative crack occurs at about three times the load which produces the first crack due to positive moment. These curves also indicate little increase in load-carrying capacity for an effective prestress greater than 300 psi. There

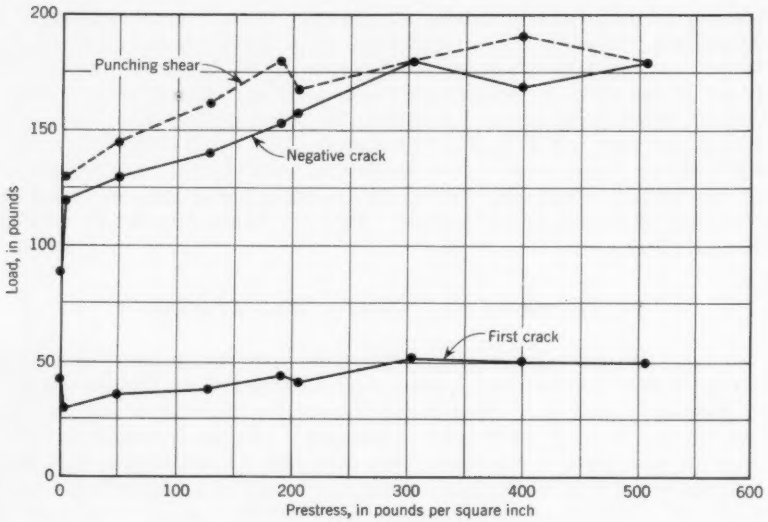

FIG. 3.—FAILURE LOAD FOR PRE-TENSIONED PRESTRESSED SLABS; 0.50 IN. RADIUS LOADING

is also some indication in the field that an optimum range of effective prestress for prototype pavements is from 200 psi to 300 psi.

The second type of model for studying the behavior of prestressed pavements is one designed for the application of repetitive traffic loading. It consists of an enclosure for constructing a subgrade of natural soils ranging from cohesive to granular materials, and a loading device for applying traffic in a predetermined pattern to a model prestressed concrete slab. The inside dimensions of the container for the subgrade are 8 ft by 17 ft by 4 ft deep. The model prestressed slabs are 15 ft by 6 ft by 1 in. thick. Effective prestress of 250 psi is provided longitudinally and transversely by 12 gauge (0.1055-in. diameter) high tensile strength stress-relieved wire with bright finish. The wire is placed at the mid-depth of the 1-in. thick slab with a spacing of 4 in.

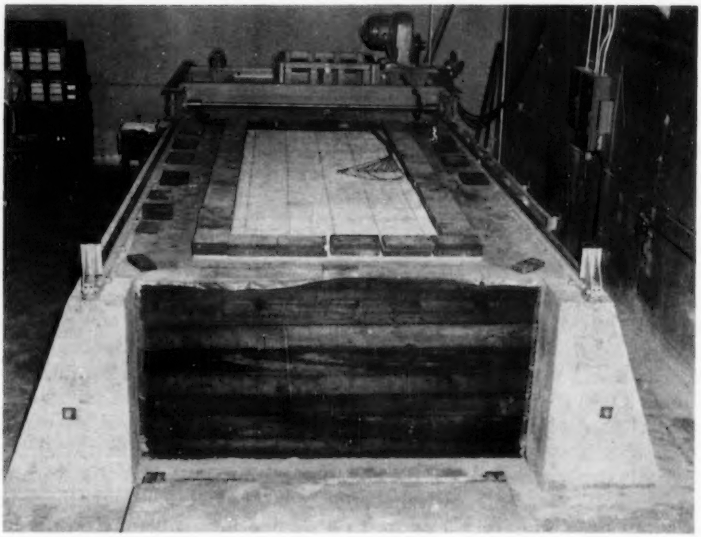

FIG. 4.—ASSEMBLY FOR REPETITIVE TRAFFIC LOADING

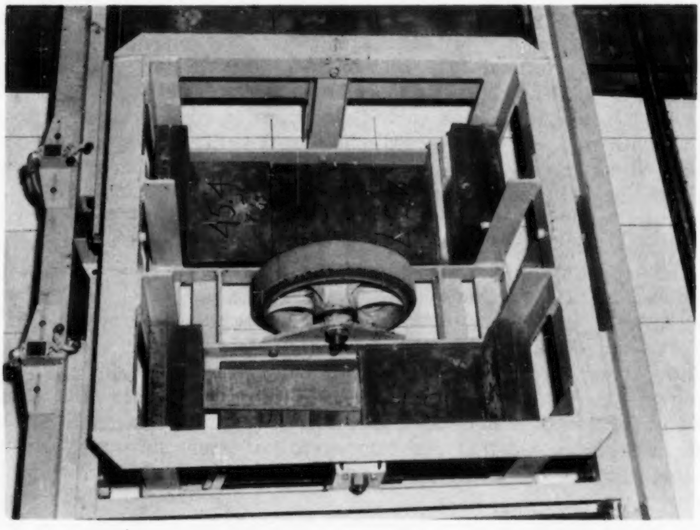

FIG. 5.—LOAD BOX AND WHEEL OF TRAFFIC LOADING DEVICE

center to center, longitudinally and transversely. The pretensioned model slabs are cast on a specially designed casting bed and are lifted into position on the prepared subgrade. The slab surface is finished to a tolerance of ±0.001 ft. Fig. 4 shows the complete assembly with the model slab on the subgrade and the loading device in the background. The subgrade in this case is a lean clay compacted to a uniform density. The modulus of subgrade reaction, k, is approximately 50 lb per cu in. The subgrade is covered with a polyethylene sheet to prevent drying. This sheet remains in place between the model slab and subgrade. The polyethylene does not completely prevent moisture content changes in the subgrade; however, the changes occur slowly and can be accounted for in the evaluation of the model's performance. The steel blocks around the outside edge of the model slab are used as dead weight to keep the slab in contact with the subgrade at all times. A part of the automatic equipment for recording strains and deflections under the moving wheel load traffic shows to the left in the background of Fig. 4. Fig. 5 shows the load box and wheel for applying the traffic loading. The load box is contained in a steel frame with rollers allowing free vertical movement. The wheel can be loaded within a range of 1,000 lb to 2,000 lb by placing steel blocks in the load box. Limit switches for controlling the transverse motion of the box are shown on the left. The traffic loading is applied uniformly to the central 2 ft of the model slab width and to within 2.5 ft of the ends. The longitudinal movement of the loading device is also controlled by limit switches. The contact area of the solid rubber tire varies from approximately 5 sq in. to 8 square in. depending on the load. For a wheel load of 1,800 lb, the contact area would be 8 sq in., giving a contact pressure of about 225 psi. The number of load repetitions is given in coverages. One coverage is applied when the load wheel traverses the central 2 ft of the model slab once. Eight to nine passes of the device, depending on the load, are required to produce one coverage.

Fig. 6 shows a typical failure of the 1-in. thick prestressed model slab. This failure occurred at 6,157 coverages of a 1,896-lb single-wheel load. The failed area is approximately 9 in. by 12 in. After the failure shown in Fig. 6 had occurred, the model slab was removed from the subgrade and the crack pattern on the underside was traced, as shown in Fig. 7. These cracks were held so tightly closed by the prestress that the slab had to be flexed slightly to be able to detect them with a magnifying glass. The traffic area, as well as the cracks, have been marked with ink. It can be seen that no cracks extend beyong the traffic area. The load was sufficient to produce cracking in the bottom of the slab at the first load application. Fig. 8 shows a portion of this same crack pattern clearly visible on the polyethylene sheet placed between the slab and the clay subgrade.

The failure in the model may be compared with a failure in a prototype pavement 9 in. thick with an effective net prestress of 130 psi longitudinally and 390 psi transversely, as shown in Fig. 9. The subgrade modulus, k, for the prototype pavement is approximately 85 lb per cu in. This failure occurred at 2,000 coverages of a 265,000-lb load on a 4-wheel twin-tandem gear assembly. It might be noted that plain concrete pavement sufficient to carry this same load for the same number of load repetitions would have to be 19.5 in. thick.

The results of the limited number of tests made with the traffic model show good correlation between model and prototype behavior. To date the information on repetitive traffic loading is limited to subgrades having moduli of sup-

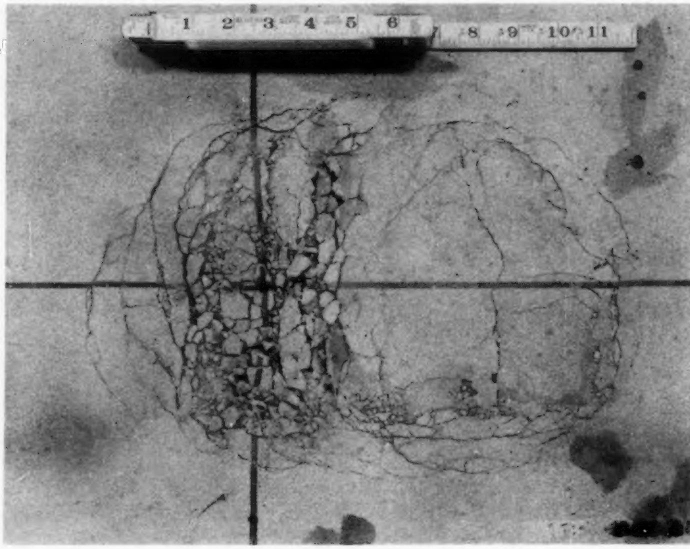

FIG. 6.—FAILURE OF 1-IN. THICK PRESTRESSED MODEL SLAB

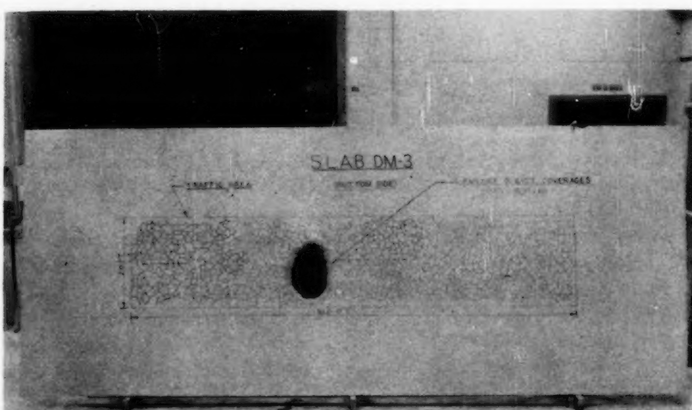

FIG. 7.—UNDERSIDE CRACK PATTERN IN TRAFFIC LOADING AREA

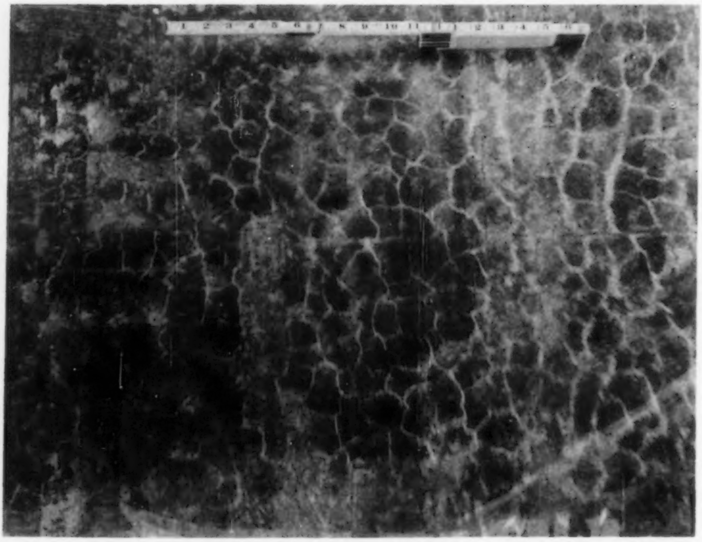

FIG. 8.—CRACK-PATTERN IMPRINT FOR MODEL SLAB

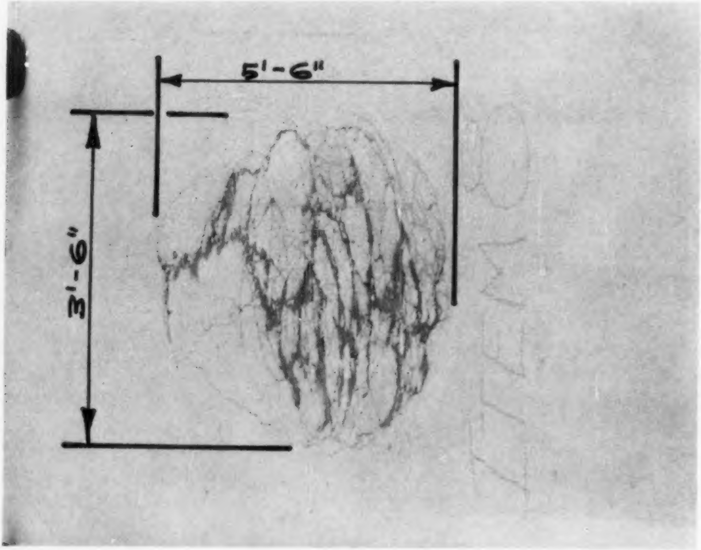

FIG. 9.—FAILURE OF FULL-SCALE 9-IN. THICK SLAB

port in the range of 50 lb per cu in. to 100 lb per cu in. It is believed that increasing this modulus will show greater benefits than are now obtained from theoretical extrapolation of data based solely on results of tests on weak subgrades. Use of the traffic model provides an inexpensive means of obtaining a wide variety of preliminary information about the effects of repetitive traffic loading under laboratory conditions. Until more conclusive information is available, the results obtained may be used directly in prestressed pavement design and will serve as a guide in planning any future full-scale traffic tests.

A METHOD OF DESIGN

Prestressed concrete pavement design, like plain concrete pavement design, must necessarily be based on empirical concepts, that is, a basic theoretical approach is modified to conform with experience and conditions falling outside the assumptions on which the theory is based. This procedure is demonstrated by the tentative design method outlined herewith:

Based on the experimental work outlined previously, the following formula for determining the required design prestress has been developed:[12]

$$R_p = \frac{6\,P\,N\left[C\,\frac{M}{P} - \frac{M_r}{P_o}\right]}{S\,h^2} - R + F \qquad (1)$$

in which P is the multiple-wheel gear load, N represents the design factor for repetitive loading, C is the moment correction factor, M/P denotes the positive moment per pound of wheel load based on the Westergaard analysis, M_r/P_o is the negative moment per pound of wheel load at a distance r from the center of load, r represents the distance from the center of the load of the maximum radial negative moment after cracking has occurred in the base of the pavement beneath the loaded area, P_o is the wheel load at which cracking occurs in the base of the pavement due to positive moment beneath the loaded area, S represents the ratio of multiple-wheel gear load to an equivalent single-wheel gear load, h is pavement thickness, R denotes the flexural strength of the concrete, and F is the maximum subgrade restraint stress.

The design factor, N, for repetitive loading has been empirically determined by correlating results of full-scale traffic loading tests on prestressed pavements with results of the model traffic loading tests. Indications are that the value of N will vary from 2.0 to 2.5 for a range of from 1,500 to 60,000 coverages. The term C is a moment correction factor evaluated from small-scale prestressed model tests. The terms M/P and M_r/P_o also are derived from the small-scale model tests. The first term of Eq. 1 gives the maximum radial stress due to the maximum negative radial moment. The term, coefficient of subgrade restraint, is a function of the weight and length of the slab.

If steel tendons are used for longitudinal prestress, there is a definite limit to the length of the slab before the steel required to overcome subgrade restraint stresses becomes excessive. Generally, when steel tendons are used

for longitudinal prestressing, it is not practical to make slab lengths greater than 600 ft.

CONSTRUCTION OF AIRFIELD PAVEMENTS

A. J. Harris[2] and D. Vandepitte[8] classify prestressed pavements as follows:

1. Pavements prestressed by tensioned steel tendons in the longitudinal directions;
2. Pavements prestressed in the longitudinal direction by means of jacks or wedges with thrust blocks to withstand the prestressing forces at the ends of the pavement. (This method stresses the slab as a unit without longitudinal steel.)

Both types of construction have been used for major taxiway and runway pavements in Europe. In the United States only the first type has been used.

The three operational prestressed airfield pavements in the United States are located at the San Antonio Airport in Texas, the Lemoore Naval Air Station in California, and Biggs Air Force Base in Texas. Complete descriptions of these pavements are available.[9] The largest in area of these three is the pavement at Biggs Air Force Base. This prestressed pavement is 1,500 ft long by 75 ft wide by 9 in. thick.

Some of the major prestressed airfield pavements outside the United States are described in the following paragraphs. They have been selected to illustrate some of the methods used in constructing the two general types of prestressed pavements.

Maison Blanche Airport, Algiers.—Built in 1954, the runway is 8,000 ft by 97 ft by 7.1 in. thick and taxiway is 6,700 ft by 92 ft by 7.1 in. thick.

This pavement is mentioned because it is the first truly commercial application of prestressed concrete for airfield pavements. The prestressed pavement was selected as an alternate to a plain concrete pavement 14.5 in. thick. It is a pavement of the second type, since longitudinal prestress was applied externally by flat jacks in active joints spaced every 1,000 ft, jacking being against elastic abutments formed by underground prestressed anchors. The prestress in both directions was 250 psi. Transverse prestress was provided by steel tendons. More complete details are available.[2,8] The largest aircraft using this pavement is the Boeing 707. At present these prestressed pavements are, to the best of the writer's knowledge, in good condition and showing no cracks or distress.

Brussels National Airport, Melsbroek, Belgium.—Built in 1959, the runway is 11,100 ft by 148 ft by 7.1 in. thick. This pavement is also of the second type because longitudinal prestress is obtained by flat jacks in joints at 361-ft intervals. Jacking is against fixed abutments at the ends of the pavement. The fixed abutments at each end of the pavement consist of a reinforced concrete slab 148 ft square and 16 in. thick. Twenty-two reinforced concrete anchor ribs approximately 16 in. thick extend 4 ft into the ground. The ribs were formed directly against the excavation. Active joints are provided with five flat jacks in each lane located over concrete lined tunnels. After initial prestressing, three jacks were removed and two left in place. These remaining two can be jacked from the tunnel if additional prestressing is required. To prevent buckling at the active joints, flexible vertical steel rods are anchored in

the pavement and invert of the concrete lined tunnel. Transverse prestress is provided by steel tendons. When this pavement was inspected in the fall of 1960, no cracks or distress were evident. This pavement also appeared to have excellent riding qualities.

Wahn Airport, Cologne, Germany.—Built in 1960, the runway is 12,464 ft by 196 ft by 7.1 in. thick, and the taxiway is 12,464 ft by 75 ft by 7.1 in. thick. This pavement is of the first type because longitudinal prestress is provided by post-tensioned steel tendons. The prestressed slabs are approximately 395 ft long with steel angle expansion joints carried on grade beams. A 3-ft gap was left at the slab ends for post-tensioning and grouting operations. This gap was filled later with reinforced concrete, leaving a 2.4-in. joint which was not sealed. This joint is covered with a steel plate. The concrete grade beams are 64 in. wide and 9 in. thick. The longitudinal prestress is 284 psi at the end of each slab and 214 psi at the center. A recent inspection of these pavements indicates that the workmanship on the runway and taxiway is good, but the steel plate joints are rough and somewhat noisy. Alternate bids were taken for both prestressed and plain concrete pavements. For this project, prestressed concrete was the cheaper.

Vienna Airport, Austria.—Built in 1959, the runway extension is 3,280 ft by 148 ft by 6 in. thick, and the taxiway is 3,609 ft by 74 ft by 6 in. thick. Although this pavement is not as extensive as those previously described, it is a unique pavement of the first type, because the longitudinal prestress is obtained by pretensioned steel tendons. The transverse prestress is provided by post-tensioned steel tendons, the conduits carrying the tendons being grouted after the tensioning is completed. The individual slabs were 400 ft long. The initial prestress was 227 psi in the longitudinal direction and 142 psi in the transverse direction. These pavements were jacked against restraining pavements or specially constructed abutments at their terminal ends by means of flat jacks in the transverse joints at 800-ft intervals. The transverse openings were then filled with reinforced concrete. The openings were filled in an effort to prevent movement at the transverse joints or reduce it to a minimum. Movement was not prevented entirely, because a seasonal opening of over 0.5 in. occurred and special sealing measures were required. Another unique feature of this pavement was the carrying of the longitudinal pretensioning tendons around a specially constructed abutment to provide for a horizontal curve in the taxiway pavement. More complete details of these pavements are available.[13,14]

PAVEMENT PERFORMANCE

In addition to the prestressed pavements at the four airfields described herein, prestressed concrete pavements have been built at at least eight other airfields in Europe. These pavements range in size from small areas of one slab length (200 ft to 400 ft) to complete runway and apron pavements. There have also been quite a few experimental prestressed concrete highway pavements built in Europe.

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13 "Pretensioned Prestressed Concrete Pavements for the Vienna Airport," by Bruno Freibauer, Proceedings, Prestressed Concrete Inst., Vol. 6, No. 1, March, 1961.

14 "Wire and Pin Anchorages Permit Pretensioning Tendons in Place," Engineering News-Record, McGraw-Hill Book Co., Inc., New York, December 17, 1959.

At the present time (1961) the chief problem with pavements having longitudinal prestressing tendons is the construction of adequate transverse joints between the 300 ft to 500 ft long slabs. This problem is created by the horizontal movement of the slab as it expands and contracts with temperature changes. Seasonal movements of 1.5 in. and daily movements of 0.5 in. have been measured at the transverse joints in the prestressed pavements at Biggs Air Force Base near El Paso, Tex., where the slabs are 500 ft long. There are two possible solutions to this problem; either (1) design a mechanical joint that will accommodate these movements or (2) reduce the movement by confinement at the terminal ends of the prestressed pavement to the point at which normal expansion seals will perform satisfactorily. An elaborate mechanical joint has been used in the transverse joints of the prestressed pavement at the Lenmoore Naval Air Station.[9] This joint has performed satisfactorily since the construction of this pavement early in 1960.

In prestressed pavement without longitudinal steel used for prestress, a large variation in prestress occurs with temperature change. At Maison Blanche it was estimated[2] that the longitudinal prestress would vary from 250 psi to 1,250 psi for temperatures ranging from 32° F to 120° F. At this field the condition of extremely high prestress was relieved by the use of elastic abutments to reduce the thrust. At Melsbroek, where fixed end abutments were used, some of the flat jacks were left in place to provide a means of maintaining a certain level prestress shouls there be loss of prestress due to creep of the abutments or other causes.

Another factor in the consideration of pavements prestressed without longitudinal steel is that, under repeated traffic loadings that stress the pavement above its elastic limit in positive moment, the lack of longitudinal steel tendons may reduce the number of load repetitions that the pavement will tolerate before failure. This question cannot be answered by theoretical considerations or by static loading tests. However, traffic loading tests under similar conditions on pavement with and without longitudinal steel may provide a satisfactory answer.

Another problem in the construction of either type of prestressed concrete pavements is the prevention of transverse shrinkage cracks when long reaches of unjointed slab are placed. This cracking can usually be overcome by using proper curing methods and by applying a small amount (75 psi to 100 psi) of prestress as soon as the concrete has hardened. If pretensioned longitudinal steel tendons are used, even better control of such cracking can be obtained, because the tendons provide definite reinforcement for the fresh concrete.[13]

CONCLUSIONS

1. At present, there are available enough results from experimental and analytical studies to design prestressed concrete and plain concrete airfield pavements that are reasonably comparable in load-carrying capacity for current military and commercial jet aircraft.

2. In Europe prestressed concrete airfield pavements appear to be competitive with plain concrete pavements and in some instances appear to be cheaper.

3. The treatment of transverse joints in pavements using longitudinal tendons for prestress needs further study and research. This has been a construc-

tion problem for the prestressed pavements of this type constructed in this country as well as for those built in Europe.

4. Further investigational work is needed to evaluate critically the performance, under repeated traffic loading, of prestressed concrete pavement that does not utilize longitudinal steel for prestress.

5. If the advantages of prestressed concrete airfield pavements are to be demonstrated in this country, a full-scale prestressed airfield runway and taxiway should be built. This would provide reliable information on first costs and, over a period of time, information on maintenance requirements and operational characteristics.

ACKNOWLEDGMENTS

The data given in this paper on model studies of prestressed pavements was obtained from current rigid pavement investigational work which the United States Army Corps of Engineers is doing for the United States Air Force.

The information on the present condition of the prestressed pavements at Maison Blanche, Melsbroek, and Wahn Airport was obtained from Gordon K. Ray, F. ASCE, Manager, Highways and Municipal Bureau, Portland Cement Association. Ray inspected these pavements during the fall of 1960.

Journal of the
AIR TRANSPORT DIVISION
Proceedings of the American Society of Civil Engineers

NEED FOR MORE AIR TERMINAL GATES

By Thomas M. Sullivan,[1] F. ASCE

SYNOPSIS

The introduction of large jet aircraft into existing terminal facilities has caused the handling of fewer planes from the existing gates. These large aircraft must be handled differently from piston aircraft because of their size and the resultant blast and noise effects.

INTRODUCTION OF JET AIRCRAFT TO EXISTING FACILITIES

When jet aircraft were introduced to terminal aprons which had been designed for piston engine aircraft, the increased size and their operational requirements raised havoc with existing gate and parking configurations. This was especially true of ramp areas that had originally been constructed to provide only modest operating clearances for the then-contemporary piston engine aircraft.

The impact on existing gate positions was a reduction in their number in relation to available terminal frontage. For example, a passenger terminal facility which only a few years ago accommodated twenty-four aircraft of DC-4, 6, 7, or L-1049 size could now provide for only sixteen to eighteen Boeing 707 or DC-8 positions (Fig. 1). This, of course, assumes that the aircraft would taxi in and out of its gate position under power. The increased physical size of the aircraft and its reduced maneuverability on the apron due to the bogie gear were responsible for larger turning radii, resulting in increased space requirements adjacent to terminal buildings.

Note.—Discussion open until January 1, 1962. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Air Transport Division, Proceedings of the American Society of Civil Engineers, Vol. 87, No. AT 2, August, 1961.

[1] First Deputy Dir. of Aviation, Port of New York Authority, New York, N. Y.

Initially, it was thought that the increased seating capacity of jet aircraft would lessen the demand for additional gate positions; however, this was not the case. Whether the reasons are ever expanding schedules, charters, extra sections, extended gate times, peaking of flights during a particular time of day or any other circumstance, experience has shown that the gate demand is almost always greater than the existing availability.

In addition to taking up more apron area, the jet has created a number of related apron problems, such as heat, noise, and blast close to passenger terminal buildings. The resulting development of proper blast deflection devices and refined apron operating procedures have insured the safety of the public and airline personnel. These devices and procedures form an integral part of the modern jet terminal.

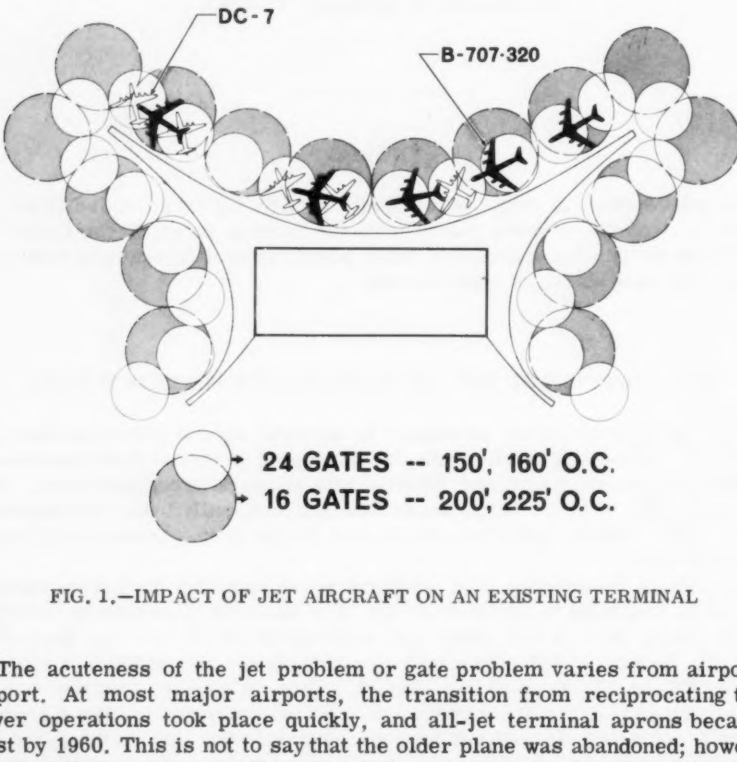

FIG. 1.—IMPACT OF JET AIRCRAFT ON AN EXISTING TERMINAL

The acuteness of the jet problem or gate problem varies from airport to airport. At most major airports, the transition from reciprocating to jet power operations took place quickly, and all-jet terminal aprons became a must by 1960. This is not to say that the older plane was abandoned; however, it meant that apron operations had to be geared to the new aircraft with the conventional ship falling in place without causing any serious problems.

The space situation became most serious in many terminal areas where available ground area could either not be expanded or could only be expanded at prohibitive costs. Where the demand for the number of gates remained the same or was only slightly increased, and where sufficient land area was available for expansion, the solution consisted of providing additional apron paving and loading finger extensions within reasonable walking distance from

the terminal proper. In some cases jet aircraft had to be positioned at the extreme end of loading fingers or ramps to minimize the related problems of heat, noise, and blast.

PASSENGER CONVENIENCE—LOADING DEVICES

It may be of interest to note an important side effect of the jet which was certainly nothing new to the planner. As American automobiles, aircraft became more luxurious, faster, and increasingly convenient. The air passenger of today expects comparable conveniences in the terminal building and would be reluctant to walk as far as 1,000 ft to the last gate on a loading finger in

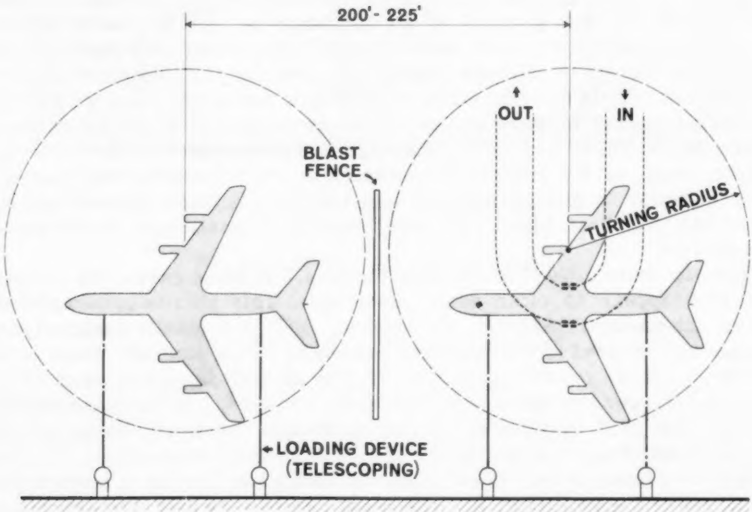

FIG. 2.—PARALLEL POSITION, POWER IN—POWER OUT

order to enter the most modern means of transportation. Therefore, the jet gate became the luxury gate and as such, should ideally be located as close to the terminal building as possible; moreover, a direct connection between the terminal and the aircraft cabin became a prerequisite. And so, the passenger loading device, after being filed away for so long, came into its own. Many carriers realized the competitive advantage of providing this passenger convenience and have incorporated it in new terminal facilities.

POSSIBLE SOLUTIONS

However, this did not solve the gate problem. In many cases, the loading device, the blast fence, and revised apron operating procedures, individually

or in combination, contributed to the only alternative—which consisted of controlling the method of positioning the aircraft at the gate. In other words, because we cannot reduce the physical size of the aircraft, we can attempt to minimize the maneuvering space normally necessary for placing the aircraft on the gate by procedures used with reciprocating aircraft. To illustrate, one might draw a parallel with the docking of an ocean liner. There too, the extremely large size of the liner and its lack of maneuverability makes it mandatory to position the ship at its berth by some other means. This is accomplished by the use of powerful tugs. The means of achieving this objective will now be reviewed and analyzed. For reasons of simplicity, these illustrations are based on the large commercial liners, such as the 707-320 or DC-8, but they actually apply to all aircraft.

Parallel Position, 220 ft to 225 ft on Centers.—This type of operation is most conventional, and consists of an "Under Power" arrival and departure utilizing the full turning radius requirements of the aircraft, in order to position the fuselage parallel to the building (Fig. 2). The plan is desirable, if sufficient terminal apron area is available, at airports serving a great number of transit or through flights, because the time required to position the aircraft is held to a minimum. Depending on the aircraft and its main gear configuration, the between-center distances of operating circles range anywhere from 200 ft to 225 ft. Passengers have access to both doors via the ground level, or for additional convenience, via a second-level loading device. In order to protect the terminal building, adjacent aircraft and apron personnel from heat, blast, and noise, blast fence installations would normally be required.

Remote Gates, 200 ft to 225 ft on Centers.—In some cases, the remote jet positions appear to offer some advantages. This plan is contemplated for Dulles International Airport, Washington, D. C. A specially designed mobile lounge will be used to transport the passenger to the aircraft, which is positioned on a large remote apron (Fig. 3). The aircraft is parked away from the terminal proper, preferably close to the runways, and the passengers are transported to it by tunnels, moving walkways, monorail, buses or a more sophisticated bus, the mobile lounge. The aircraft themselves may be arranged in groups of four to six about a building satellite or in large numbers on a remote apron (Fig. 4). The main reasons for this plan are the unrestricted movement of jet aircraft, the lack of space in close proximity to the terminal building, and the desire to eliminate the need for loading fingers, loading devices, or blast fencing. In some cases, partial adoption of this concept may be desirable. For example, a terminal facility may be adequate to satisfy the gate demand during most hours of the day, except perhaps for peak conditions that occur once or twice a week during certain seasons. It may prove much more practical and economical to bus some passengers to remote positions than to expand the terminal for such peak conditions. The space requirements here also range from 200 ft to 225 ft between aircraft.

Power-In Arrival—Push-Out Departure—90° Position, 170 ft to 185 ft on Centers.—This operation reflects the first departure from the conventional procedure in that it decreases the gate size to the physical limits of the jet's wing span plus a reasonable clearance from an adjacent aircraft. Under this procedure, the aircraft taxis into its position under power, nose in, 90° to the building (Fig. 5). The passengers may be loaded via apron level or loading devices to one or two doors depending on the convenience desired. If loading

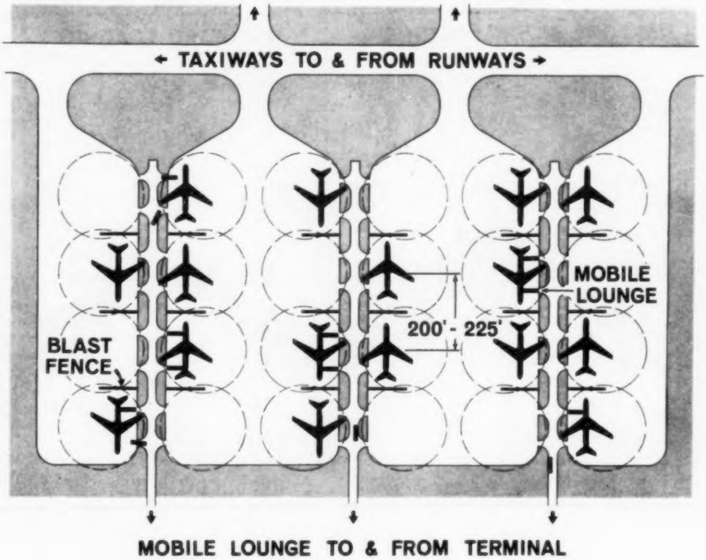

FIG. 3.—REMOTE AIRCRAFT APRON

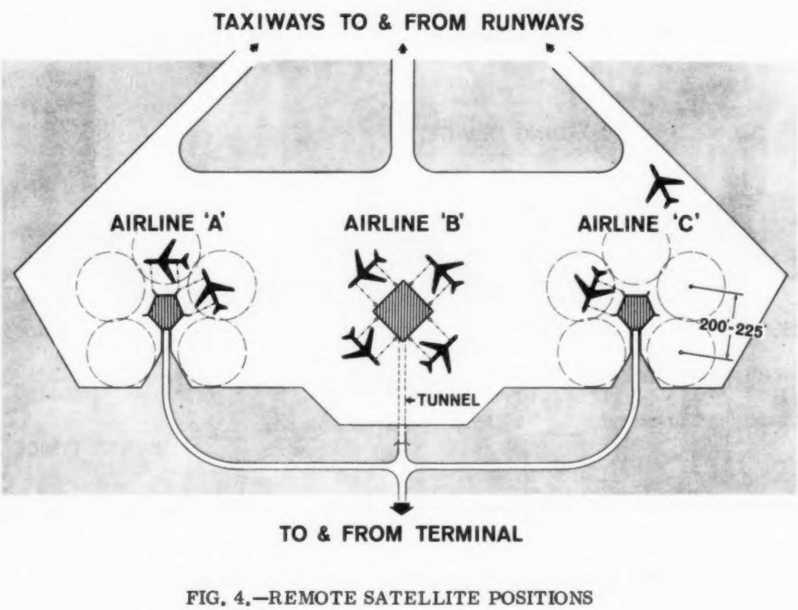

FIG. 4.—REMOTE SATELLITE POSITIONS

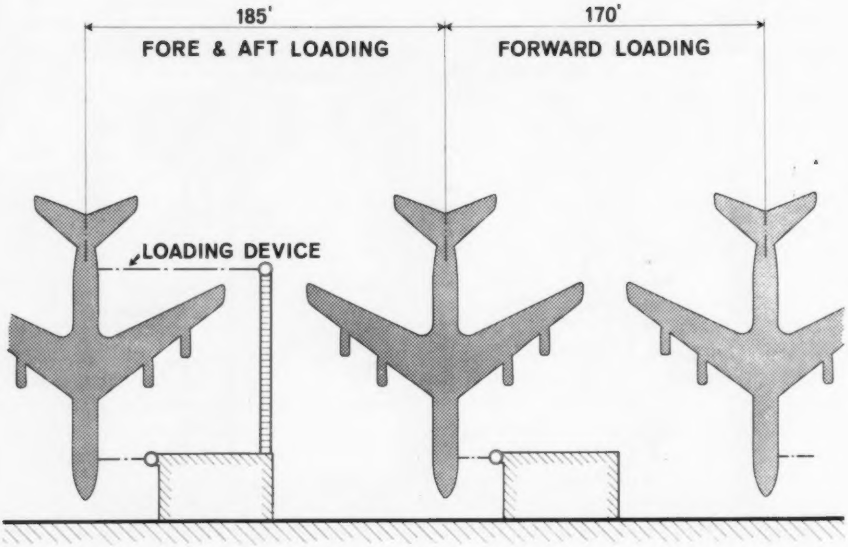

FIG. 5.—NOSE IN POSITION, POWER IN—POWER OUT

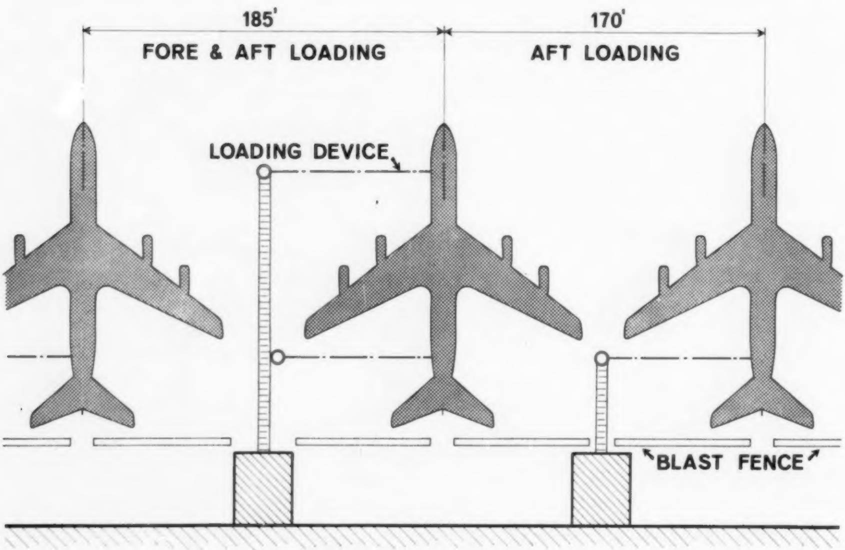

FIG. 6.—NOSE OUT POSITION, POWER IN—POWER OUT

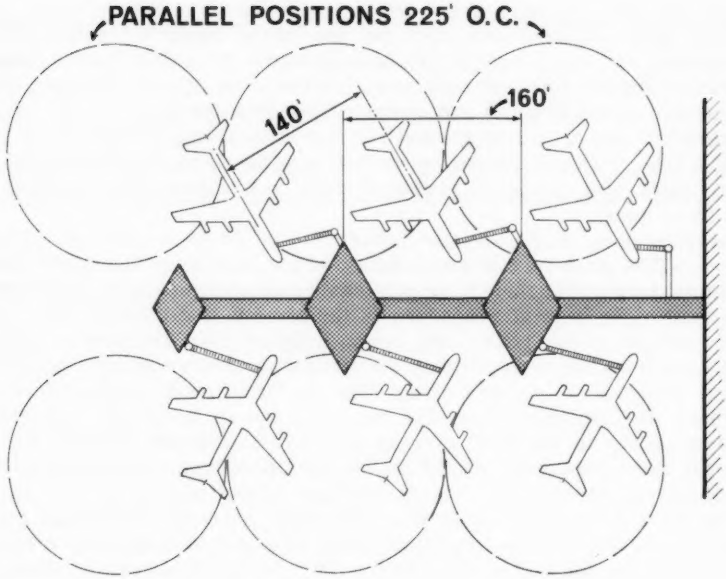

FIG. 7.—POWER IN—PUSH OUT, 60°; NOSE IN ARRIVAL, FORWARD UNLOADING; PUSH OUT DEPARTURE, FORWARD LOADING

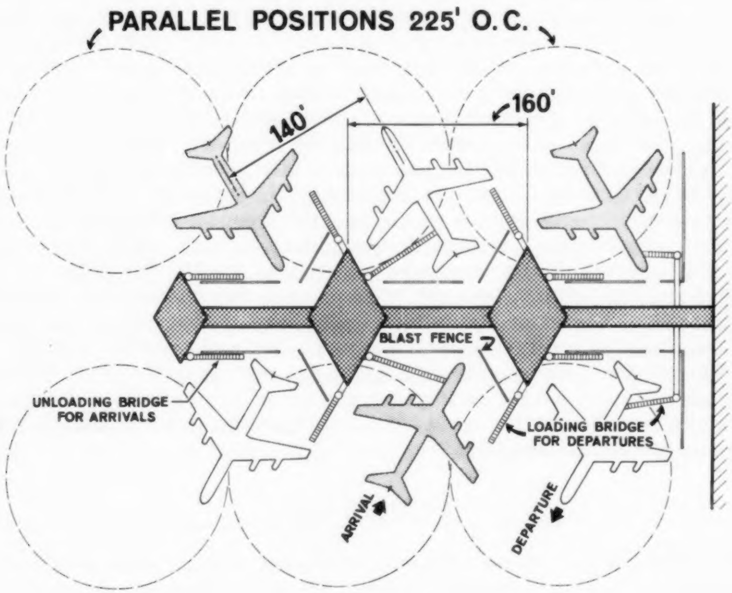

FIG. 8.—POWER IN—POWER OUT, 60°; NOSE IN ARRIVAL, FORWARD UNLOADING; NOSE OUT DEPARTURE, AFT LOADING

devices are used, passengers will not be exposed to the elements, noise, heat, or blast from adjacent aircraft, and the apron itself is free for aircraft maneuvering and ramp equipment. As soon as the aircraft is loaded, engines are started and the ship is pushed out by tractor to an adjacent taxiway. There the tractor is disconnected and the jet proceeds under power to the runway. The push-out and tractor disconnecting operation normally takes from 1 1/2 min to 2 min. Gate spacing varies according to the desire to unload from one or two doors with or without loading devices, and is generally from 170 ft to 185 ft on centers.

Power-In Arrival—Power-Out Departure—90° Position, 170 ft to 185 ft on Centers.—This procedure is a refinement of the previously discussed power-in, push-out operation, but it is applicable only where certain conditions or needs exist. The arrival procedure is the same in that the aircraft is positioned nose in, under power, 90° to the building. Now, in order to assure a speedy and most direct departure, the aircraft is positioned with tugs before loading, nose out, 90° to the building (Fig. 6). With proper blast protection to the rear, the departure may then be under power. In the case of transient flights or cases in which an aircraft arrives at a specific gate and remains there for later departure, it may not be feasible to turn the aircraft 180° for an under power departure. However, when an aircraft arrives at one gate and departs from another, or, as in many instances, when the ship comes from a hangar or parking area, a departure of this type certainly appears desirable. The gate spacing for this method is from 170 ft to 185 ft on centers, depending on the choice of passenger loading.

Power-In Arrival—Power-Out Departure—60° Position, 160 ft on Centers.—The last of the possible gate configuration schemes to be discussed is the angle concept. The fuselage is positioned at an angle of 60° to the building (Figs. 7 and 8). As in the aforementioned procedure, this operation reflects the possibility of a power-in arrival and a power-out or push-out departure, with one basic difference. Here we have assumed that if passenger convenience demands the provision for second-level loading, it could be restricted to one door in the interest of minimum gate spacing and maximum apron utilization. Arriving passengers would unload through the front door, first class passengers, if aboard, first. Departing passengers will load through the same door, or in the case of the power-out departure, via the aft door where the first class passenger could remain in the cocktail lounge a little longer and load last. This single-door loading and unloading concept may definitely be more attractive with the smaller type aircraft, such as the 707-120, 720, 727, CV-880, 990. As indicated previously when mention was made of the 90° power-out procedure, the same limitations apply here in that the method is most practical when the aircraft is departing on an originating flight. Depending on the terminal and apron configuration, the 60° angle may also offer the additional advantage of easing taxiing movements of the arriving and departing aircraft by eliminating 90° turns. The gate spacing required under this system could be as little as 160 ft.

CONCLUSIONS

The choice of gate concept depends, to a large extent, on the configuration of existing aprons and terminal buildings, on an evaluation of passenger convenience in relation to local conditions such as weather, type of passenger, competition, operating preference and, of course, economics.

Journal of the
AIR TRANSPORT DIVISION
Proceedings of the American Society of Civil Engineers

PARKING AND CIRCULATION OF VEHICULAR TRAFFIC AT AIRPORTS

By Israel Gilboa[1]

SYNOPSIS

Vehicles create various problems at major airports. Methods and procedures for studying and evaluating these problems are indicated. The facilities required to solve the problems and the locations for such facilities are discussed. The material can be used as a general guide for the development of essential data pertinent to any airport.

INTRODUCTION

Each airport has its individual characteristics and local problems, and therefore its specific solutions. Circulation and parking requirements are affected by the geographic location of the airport, its layout and size, the character of the area it serves, the ratio of vehicle registration to population, the local driving habits, and the availability of highway and transportation facilities. For example, the ratio of cars parked to peak-hour air passengers was found, for similar size airports, to vary from 0.9 to 1.7. Thus, it is difficult to arrive at a specific standard for parking demand at airports. Studies should be conducted to determine the extent and type of vehicular parking and circulation requirements for each airport. An analysis of the results of these studies would indicate the best design of parking and circulation facilities.

Note.—Discussion open until January 1, 1962. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Air Transport Division, Proceedings of the American Society of Civil Engineers, Vol. 87, No. AT 2, August, 1961.

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The Problem.—All air travel involves various modes of ground transportation. The large jet planes placed in service during the past few years have introduced satisfactory speeds for the air portion of a trip. On a trip between downtown San Francisco and downtown Los Angeles, however, less than half the time is spent in the air. In the future, when supersonic planes will be used commercially, a similar disproportion may exist on transcontinental and intercontinental trips.

Airport operators and the commercial airlines are developing facilities to expedite the handling of passengers and baggage within the terminals. Electronic ticketing, conveyor belts for baggage, direct second-floor-level loading and unloading of planes, are some of the innovations that will assist in solving problems within the terminal. The ground transportation of people and goods to and from the airports remains a major problem, however, and associated with it are the circulation and parking of vehicles at the airport.

A vehicle arriving at an airport may wish to reach the terminal building, parking facilities, maintenance shops, air cargo buildings, or other service buildings. At airports with several terminal buildings, traffic movements must be accommodated between the various buildings as well as between the terminals and other facilities in the airport. A practical roadway and pedestrianway system must be designed to fit all circulation needs.

Adequate parking facilities must be provided for the various users—general public, valet service, employees, taxis, buses, and service vehicles. Each category of parking has specific requirements. Questions that must be answered include: how many spaces are required for each category; what type of facilities; where to locate each facility; which parking categories can be combined into a single facility; and how to control parking.

Fig. 1 shows the location of San Francisco Airport in relation to the surrounding cities, and includes the existing and proposed major highway facilities. Some 3,500,000 people reside in the Bay Area, served by San Francisco International Airport, Oakland International Airport, and San Jose Municipal Airport. San Francisco Airport serves over 90% of the total volume—some 5,000,000 air passengers in 1960.

Access Highways.—Bayshore Freeway provides the main access to the airport, connecting it directly to downtown San Francisco, all the Peninsula cities, the East Bay area via the Bay Bridge and the San Mateo Bridge, and to the North Bay via the Golden Gate Bridge. A parallel facility, Junipero Serra Freeway, is now (1961) under construction, and the Bay Front Freeway will be constructed at a future date. Two projected cross-county freeways, the San Bruno Freeway and the 19th Avenue Freeway, will also serve the airport.

Travel time for the 15 mi from downtown San Francisco to the airport varies from 20 min to 30 min depending on traffic conditions.

Public Transit.—Experience in several cities indicates that air passengers generally do not use public transit; this is the case at San Francisco Airport. Some airport employees use a bus line, which traverses the airport area, and the railroad which passes close to it.

STUDIES, ANALYSES, AND PROJECTIONS

Studies were made of vehicular traffic volumes, pedestrian volumes, parking demand, public ground transportation, and air passenger volumes. Avail-

able reports and other data pertaining to these subjects were reviewed. Information on current and past operations was then analyzed and projected to develop future requirements.

Air Passengers.—It may be expected that, in general, vehicular and parking requirements will increase in direct proportion to increases in number of air passengers. Studies at San Francisco Airport indicated such a relationship. It is estimated that air passengers will double to 10,000,000 by 1970, and will increase to 15,000,000 by 1980, when the ultimate capacity of the airport will be reached. These passenger estimates were used in determining future traffic and parking requirements.

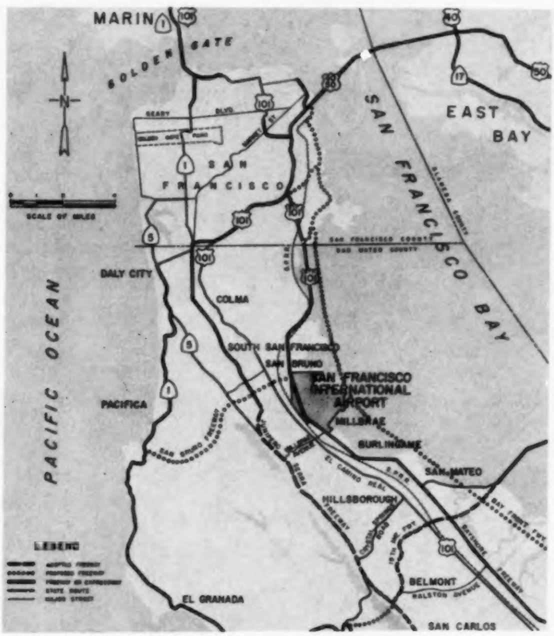

FIG. 1.—LOCATION MAP OF SAN FRANCISCO INTERNATIONAL AIRPORT

It would not be feasible to provide facilities within the terminal area for the short periods of maximum peak demand which occur only a few times a year. In the design of highway facilities, it is common practice to use the 30th highest peak hour of the year as the design hour. Similar practice should be followed in planning vehicular facilities at airports. In San Francisco Friday, May 27, 1960, during the Memorial Day weekend, was established as the design day. On this day, 17,500 enplaning and deplaning passengers were served at the airport, an increase of approximately 50% over an average day. Records of airppassengers at the airport have indicated that during the year there are approximately 30 days on which a greater number of air passengers are served.

Parking.—Existing facilities at the airport, including the parking lots and the roadway system, are shown in Fig. 2. There are 4,650 parking spaces, of which 3,500 are used for public and valet parking.

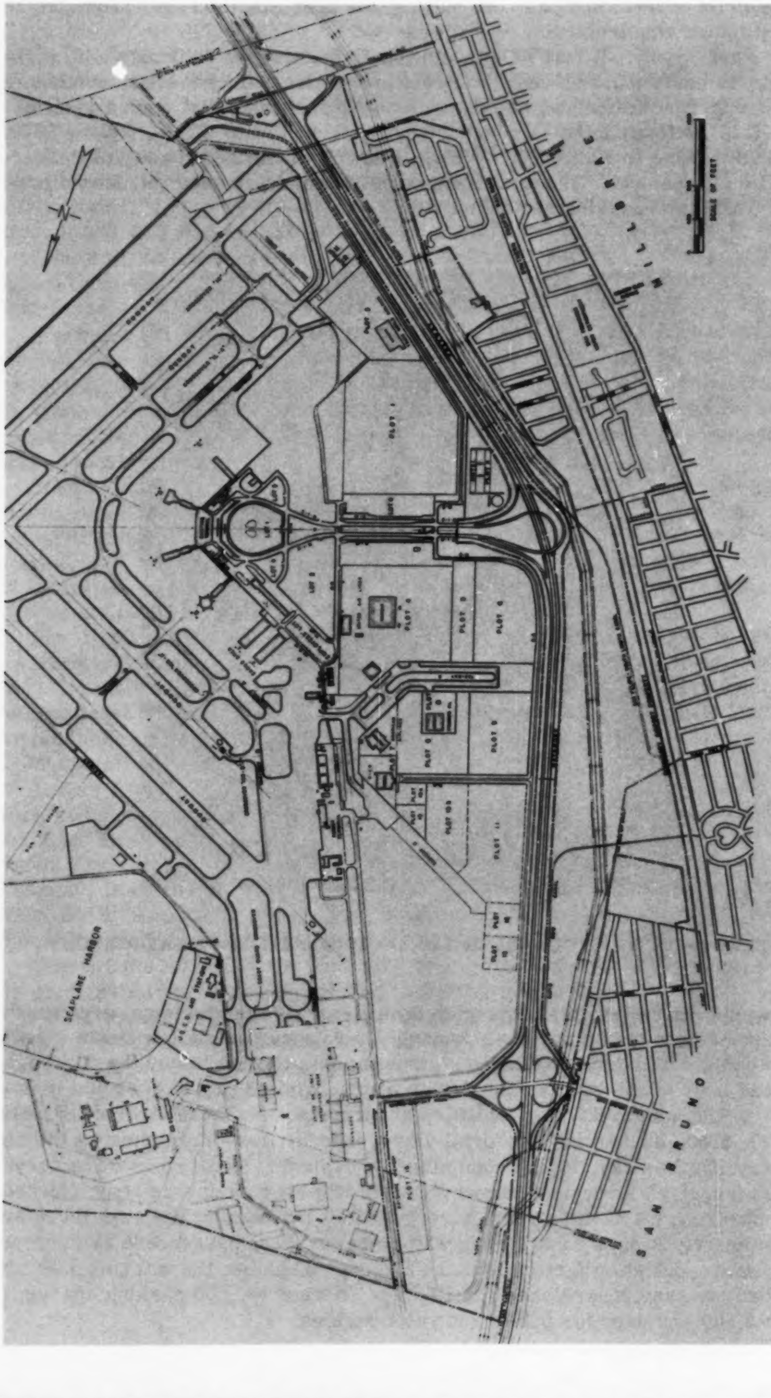

FIG. 2.—EXISTING FACILITIES AT SAN FRANCISCO INTERNATIONAL AIRPORT

A check of parking ticket receipts from public and valet parking during a 24-hr period revealed that the majority of the cars, some 60%, were parked for less than 2 hr. Patrons parking for 1 day or more accounted for approximately 12% of the total parkers. It is important to note that this relatively small group of long-term parkers absorbed almost 40% of the space-hour capacity of the parking lots.

Starting at 12:01 A.M. of the design day, the number of vehicles entering and leaving the public and valet parking areas, was counted during each hour. At 6:00 P.M. the parking facilities were photographed from a helicopter and the number of cars parked were counted from the photograph. By adding and subtracting the entering and leaving cars, there was determined a total showing the number of cars accumulated each hour of the 24-hr period.

The hourly distribution of vehicles entering and leaving public and valet parking spaces, as well as the accumulation of the design day are illustrated in Fig. 3. The peaks occurred between 5 P.M. and 6 P.M., when 500 vehicles entered; and between 7 P.M. and 8 P.M., when 570 vehicles departed. Maximum accumulation occurred between 5 P.M. and 6 P.M., when there were 2,300 parked vehicles.

The agencies providing ground transportation furnished tabulations of the number of U-Drive cars, taxis, and airport buses entering and leaving their terminal parking facilities, each huor, on the design day.

Analysis indicated that all existing parking facilities were operating at their practical capacity. Therefore, the total number of spaces was considered to represent the present demand. The projection of future parking needs was based on the anticipated increase in air passengers. It was estimated that present parking demand will triple by 1980, except for U-Drive cars.

Based on the operating experience of the past few years, it was estimated that space requirements for U-Drive cars will increase by 25% per year during the next five years, and will follow proportionately the increase in air passengers after 1965.

Vehicular Traffic.—Automatic recording counters were placed on all roads within the airport proper for 24-hr or more. The data collected were summarized and the traffic flow map, Fig. 4, was prepared, showing the 24-hr volumes on a typical day in May 1960. It was found that, during the 24-hr period, approximately 10,000 vehicles entered and 10,000 departed from the terminal area via the Airport Interchange and an additional 7,000 vehicles used in San Bruno Interchange. On the design day approximately 50% more vehicles entered and departed from the terminal area than on a typical day. Daily vehicular volumes at the existing terminal building were approximately 6,000 on the lower roadway and 3,600 on the upper roadway.

Peak-hour traffic volumes, amounting to approximately 10% of the daily volumes, occurred between 7 P.M. and 8 P.M. It was estimated that on the average the present traffic volumes on the airport roads will triple by 1980, in accordance with anticipated increase in air passengers. The peak-hour volume of 1,500 vheicles which was observed on the main entrance road on the design day will thus increase to 4,500 vehicles per hr in 1980. The estimates of future traffic were used in determining the number of lanes required on the roadway system.

Manual counts were made of vehicle classification and vehicle occupancy. These were used in determining capacity requirements of roadways and pedes-

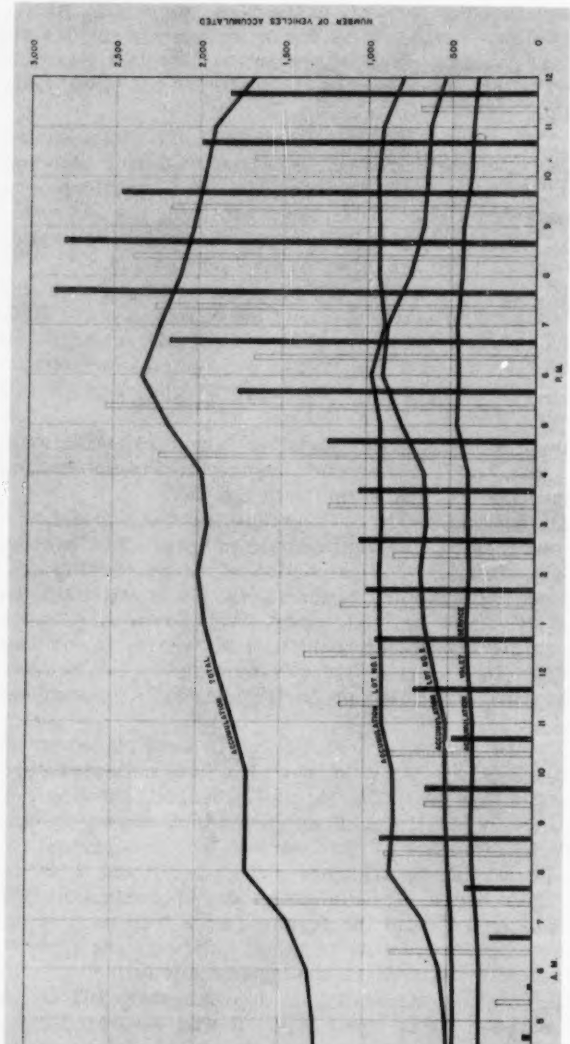

FIG. 3.—VEHICLE ARRIVALS, DEPARTURES, AND ACCUMULATION AT PUBLIC PARKING FACILITIES AT SAN FRANCISCO INTERNATIONAL AIRPORT

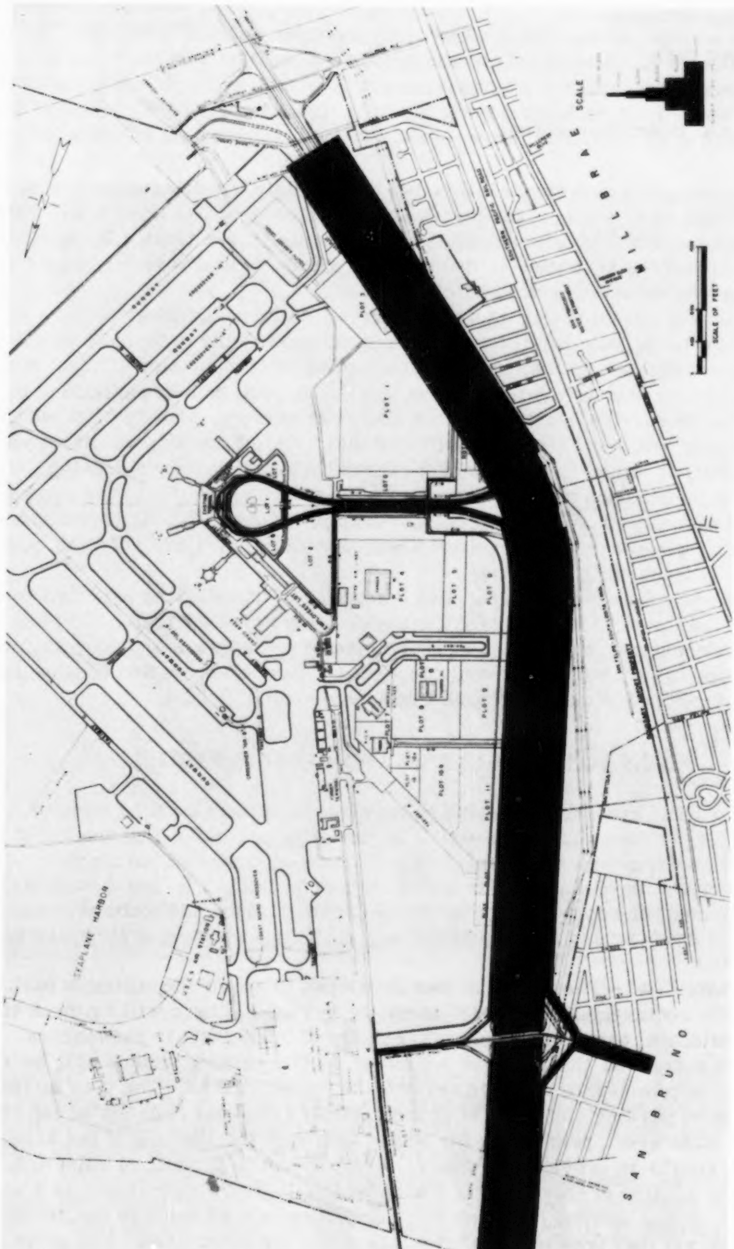

FIG. 4.–DAILY VEHICULAR FLOW IN 1960 AT SAN FRANCISCO INTERNATIONAL AIRPORT

trianways. The average results of the study are as follows:

Type of Vehicle	%	Average Occupancy, Persons per Vehicle
Passenger cars	86	1.7
Taxis	7	1.8
Trucks	5	1.1
Airport and interurban buses	2	20.0
	100	

A license-plate survey was conducted to ascertain the destination and route of passenger cars entering the terminal area. License-plate numbers of vehicles were recorded by persons stationed at strategic locations. By matching the plate numbers recorded at the several points, it was possible to plot the route that the vehicle traveled within the airport.

The survey revealed that approximately one-third of the entering cars went directly to the parking facilities; one-tenth stopped at the terminal building to deliver passengers and then entered the parking lots; one-third stopped at the terminal to serve passengers and then left the airport; and the remainder proceeded to the service courts, U-Drive, and valet service. A study of passenger cars leaving public parking lots indicated that 85% left the airport directly and 15% passed, or stopped, in front of the terminal building before leaving. The foregoing information was used as a basis for assigning traffic to the proposed roadway system. It was assumed, for example, that of the 1980 peak-hour traffic that would enter the terminal area, one-third, or 1,500 vehicles, would go directly to parking facilities.

Pedestrian Crossings.—A count of pedestrians crossing the lower roadway between the terminal building and the parking lot revealed that 1,900 persons crossed during the peak hour. Such a volume of pedestrians crossing at grade contributes to vehicular delay and congestion. Grade separation of crossings would protect pedestrians and would reduce vehicular delays.

PLANS FOR CIRCULATION AND PARKING FACILITIES

The highway and parking facilities required to satisfy existing demand may involve large capital expenditures. It is essential, therefore, that the facilities provided conform with the plans for ultimate development of the airport. The findings of the foregoing studies and analyses projected to the future target year provided the basic data for the development of plans and recommendations for future roadway and parking facilities, including a program for stage construction.

Ultimate Plan.—The plan that was developed to serve the ultimate parking and traffic requirements, for 1980 is shown in Fig. 5. There will be three terminal buildings, each with an annual capacity of 5,000,000 air passengers.

It was estimated that by 1980 a total of 14,000 parking spaces will be required to accommodate vehicles serving the terminal area. The plan includes a four-level parking sturcture of approximately 8,000-car capacity in the central terminal area, principally for public use; and the decking of the existing service courts to provide 700 spaces for operational parking of valet and U-Drive Cars. Use of these courts for valet and U-Drive operations is a convenience to the patrons, because these facilities are adjacent to the terminal buildings, yet they free terminal frontage space for other uses. The proposed

southwest court will accommodate 100 taxis and airport buses, and the northwest court will serve 100 U-Drive vehicles. Service vehicles will also utilize these courts.

The remaining parking requirements, some 5,100 spaces, will be satisfied by a 35-acre parking facility, not contiguous to, but as near as possible to the terminal area, for storage of U-Drive cars, taxis and buses, employees' cars, and overflow of public parking. It would not be feasible to provide parking facilities within the terminal area for these needs. U-Drive cars are usually

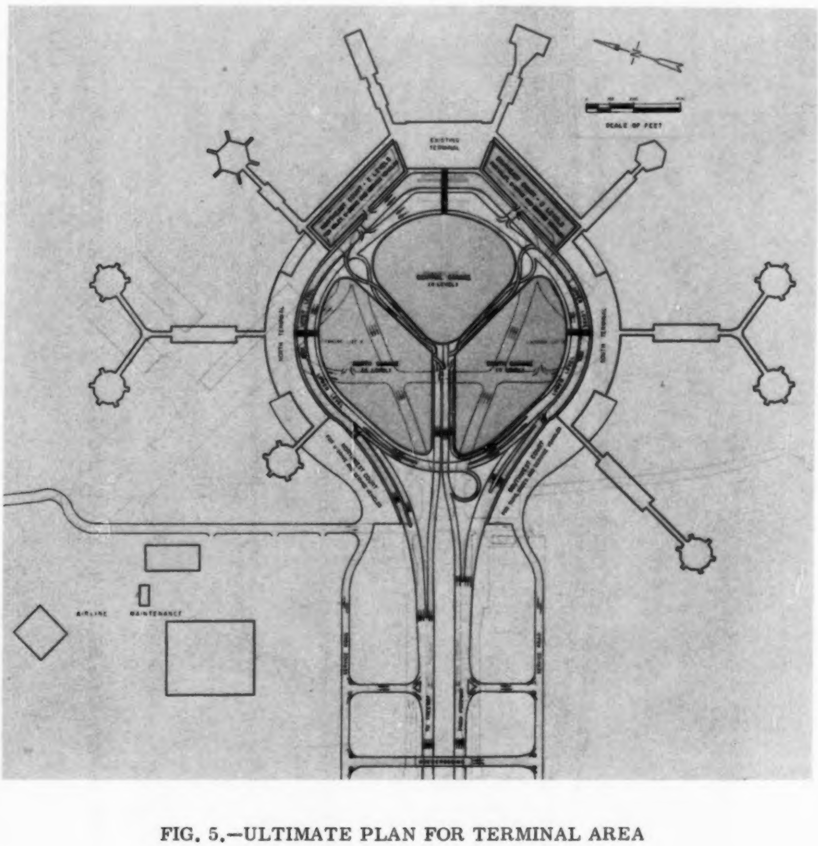

FIG. 5.—ULTIMATE PLAN FOR TERMINAL AREA

stored for long periods of time, and therefore, need not be close to the terminal building. Shuttle service will be required for the employees who arrive and depart at certain shift changes, and for public parking overflow, which is expected to occur only during a few peak days of the year.

The main roads within the terminal area are recommended as controlled-access, one-way roadways, to avoid delay and congestion and provide maximum safety. Intersecting main flows of vehicles and points of pedestrian-vehicle

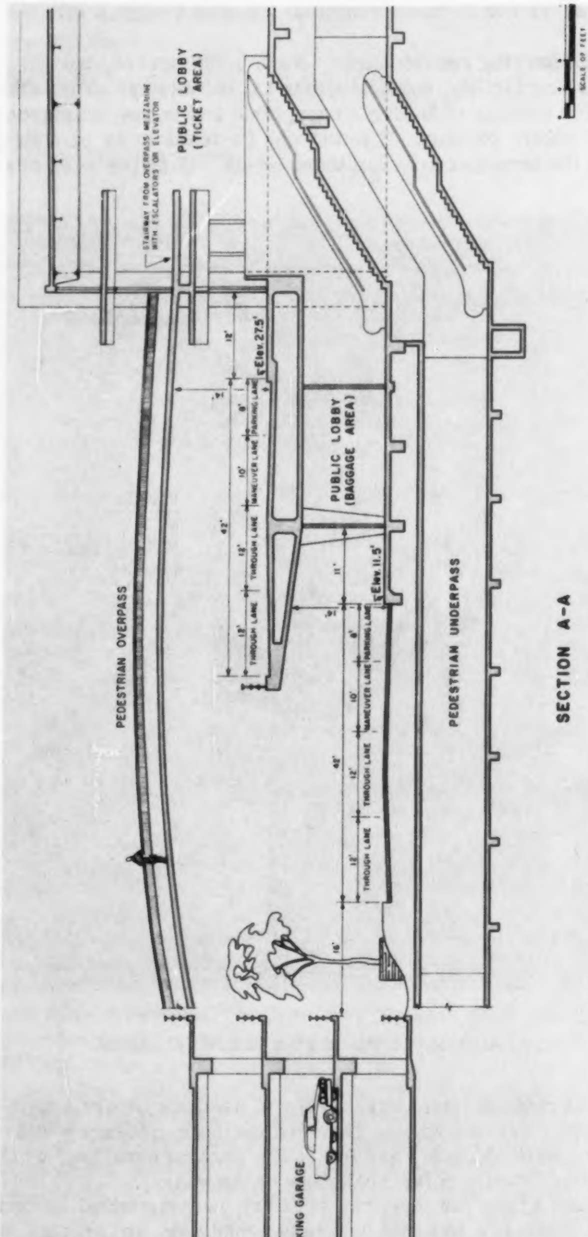

FIG. 6.—TYPICAL SECTION OF PARKING GARAGE AND ROADWAYS

conflicts are grade separated. Two circular roadways—one at the ground level and the other at the upper level—occupy the space between the parking garage and the terminal buildings. Ramp connections are provided between the two levels and between each level and the parking facilities. The main access roadways, running between Bayshore Freeway and the terminal area, connect with each roadway level. Because the majority of parkers desire to go directly to the parking facilities, direct and convenient access was also provided between the main access roadways and the garage. A north-south overcrossing structure between parallel service roads, in addition to ramps, serves all

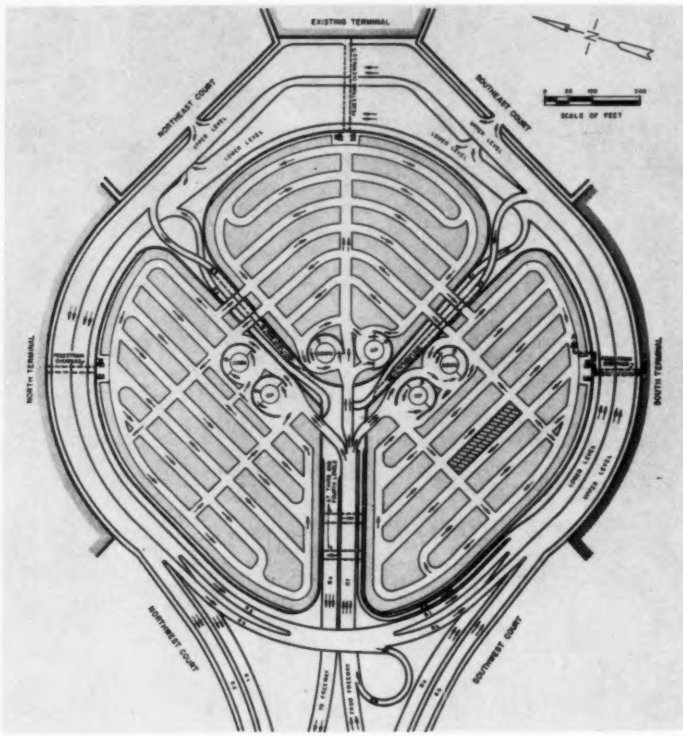

FIG. 7.—PROPOSED SECOND LEVEL OF PARKING GARAGE

movements to and from the main access roads. Complete circulation is provided within the terminal complex, allowing vehicles to circulate on each level or to change levels. Because of the many facilities contemplated within the area, the proper design and placement of directional signs will be of utmost importance.

The typical roadway section in front of and between the terminals is shown in Fig. 6. Each roadway provides two 12-ft through lanes, one 10-ft maneuver-

ing lane, and an 8-ft parking lane. These lanes are adequate to serve the projected hourly volumes of approximately 1,500 vehicles per roadway. The typical section also shows the open deck parking garage and pedestrian overpasses and underpasses connecting it to the terminal buildings.

The four-level parking garage, shown in Fig. 7, was proposed for location in the center, because this was the only available space within convenient walking distance of the terminal buildings. The alternative was to accommodate the public in parking lots farther away from the terminal and to provide shut-

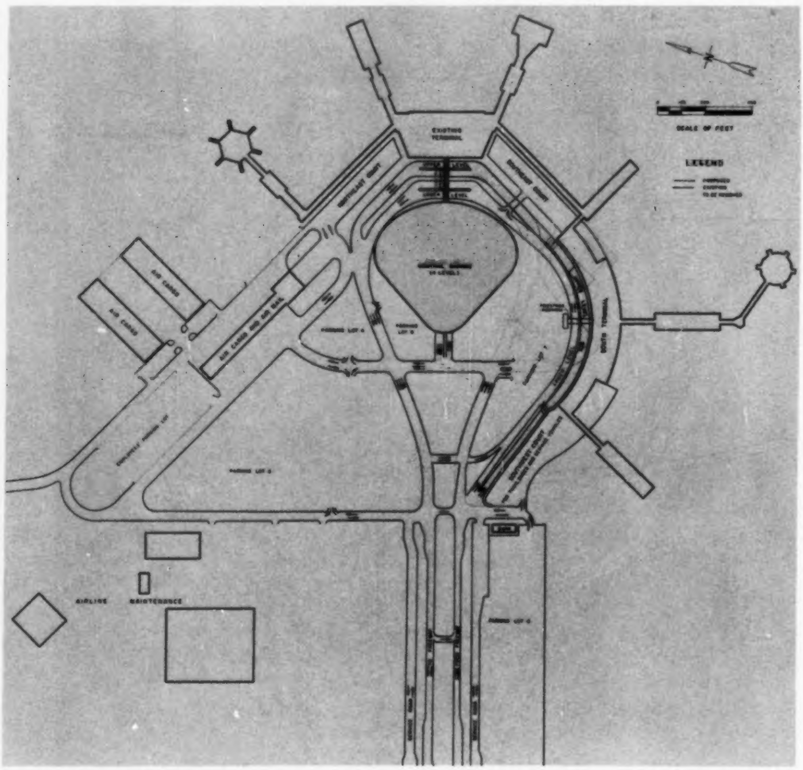

FIG. 8.—FIRST STAGE PLAN OF TERMINAL AREA

tle service. It was decided that in the interest of expedient operation and convenience to the public, parking should be adjacent to the terminal. The garage is divided into three segments, one opposite each terminal building, to allow for stage construction and to suit the siting of the terminal buildings.

Stage Construction.—Plans for stage construction comply with the ultimate development plan. The first-stage plan as shown in Fig. 8 indicates the roadways and parking facilities required in 1963, the first year of operation of the

south terminal. Approximately 6,100 parking spaces will be required to accommodate patrons of the terminal area. It was recommended that the central segment of the proposed parking garage be constructed, and that the lower and upper roadways in front of the south terminal be built and extended to connect with the present roadways in front of the existing terminal.

The recommended roadway and parking facilities included in the second-stage plan, and shown in Fig. 9, are those required to serve 10,000,000 air

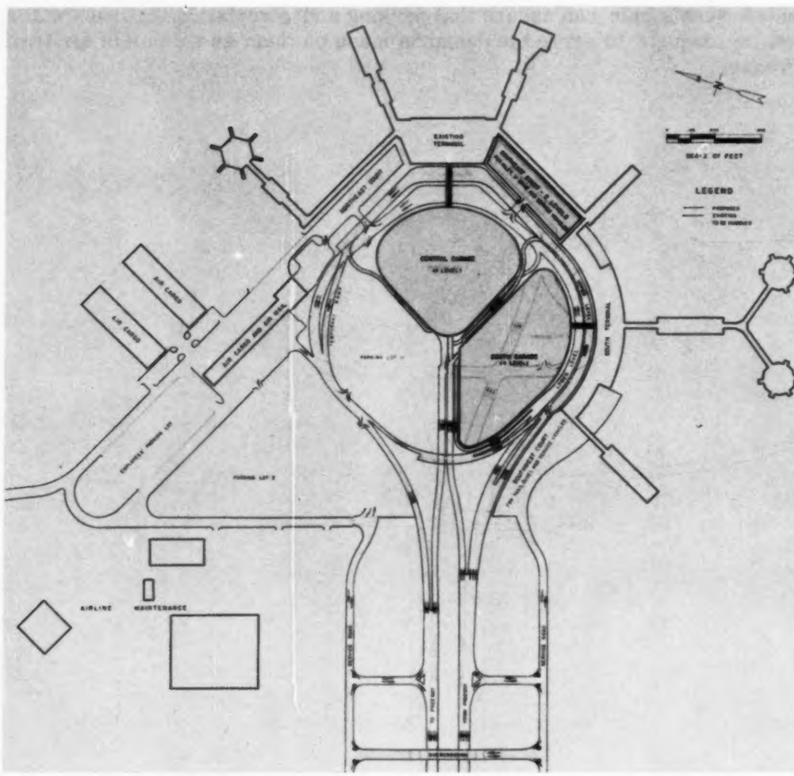

FIG. 9.—SECOND STAGE PLAN OF TERMINAL AREA

passengers per year. A total of 10,000 parking spaces is required, of which 5,300 would be located in the central and south segments of the garage.

CONCLUSIONS

Parking and circulation of vehicular traffic already create serious problems at major airports. With the continuous increase in air traffic volumes, medi-

um size airports may also be faced with similar vehicular problems in the futures. These problems will become relatively more important as air speed increases, and ground transportation time becomes a larger portion of total trip time.

Planning and design of vehicular facilities must be based on facts and sound projections. Most of the study and analysis techniques required are adaptations of established and tested standard traffic engineering procedures. A careful study by competent engineers produces a stage construction plan that directs capital expenditures in an orderly, coordinated way. Properly implemented, such a plan can assure that parking and circulation facilities will always be adequate to serve the demands made on them as volume of air traffic increases.

PROCEEDINGS PAPERS

The technical papers published in the past year are identified by number below. Technical-division sponsorship is indicated by an abbreviation at the end of each Paper Number, the symbols referring to: Air Transport (AT), City Planning (CP), Construction (CO), Engineering Mechanics (EM), Highway (HW), Hydraulics (HY), Irrigation and Drainage (IR), Pipeline (PL), Power (PO), Sanitary Engineering (SA), Soil Mechanics and Foundations (SM), Structural (ST), Surveying and Mapping (SU), and Waterways and Harbors (WW), divisions. Papers sponsored by the Department of Conditions of Practice are identified by the symbols (PP). For titles and order coupons, refer to the appropriate issue of "Civil Engineering." Beginning with Volume 82 (January 1956) papers were published in Journals of the various Technical Divisions. To locate papers in the Journals, the symbols after the paper number are followed by a numeral designating the issue of a particular Journal in which the paper appeared. For example, Paper 2703 is identified as 2703(ST1) which indicates that the paper is contained in the first issue of the Journal of the Structural Division during 1961.

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AUGUST: 2564(SM4), 2565(EM4), 2566(ST8), 2567(EM4), 2568(PO4), 2569(PO4), 2570(HY8), 2571(EM4), 2572(EM4), 2573(EM4), 2574(SM4), 2575(EM4), 2576(EM4), 2577(HY8), 2578(EM4), 2579(PO4), 2580 (EM4), 2581(ST8), 2582(ST8), 2583(EM4)c, 2584(PO4)c, 2585(ST8)c, 2586(SM4)c, 2587(HY8)c.

SEPTEMBER: 2588(IR3), 2589(IR3), 2590(WW3), 2591(IR3), 2592(HW3), 2593(IR3), 2594(IR3), 2595(IR3), 2596 (HW3), 2597(WW3), 2598(IR3), 2599(WW3), 2600(WW3), 2601(WW3), 2602(WW3), 2603(WW3), 2604(HW3), 2605(SA5), 2606(WW3), 2607(SA5), 2608(ST9), 2609(SA5)c, 2610(IR3), 2611(WW3)c, 2612(ST9)c, 2613(IR3)c, 2614(HW3)c.

OCTOBER: 2615(EM5), 2616(EM5), 2617(ST10), 2618(SM5), 2619(EM5), 2620(EM5), 2621(ST10), 2622(EM5), 2623(SM5), 2624(EM5), 2625(SM5), 2626(SM5), 2627(EM5), 2628(EM5), 2629(ST10), 2630(ST10), 2631(PO5)c, 2632(EM5)c, 2633(ST10), 2634(ST10), 2635(ST10)c, 2636(SM5)c.

NOVEMBER: 2637(ST11), 2638(ST11), 2639(CO3), 2640(ST11), 2641(SA6), 2642(WW4), 2643(ST11), 2644(HY9), 2645(ST11), 2646(HY9), 2647(WW4), 2648(WW4), 2649(WW4), 2650(ST11), 2651(CO3), 2652(HY9), 2653(HY9), 2654(ST11), 2655(HY9), 2656(HY9), 2657(SA6), 2658(WW4), 2659(WW4)c, 2660(SA6), 2661(CO3), 2662(CO3), 2663(SA6), 2664(CO3)c, 2665(HY9)c, 2666(SA6)c, 2667(ST11)c.

DECEMBER: 2668(ST12), 2669(IR4), 2670(SM6), 2671(IR4), 2672(IR4), 2673(IR4), 2674(ST12), 2675 (EM6), 2676(IR4), 2677(HW4), 2678(ST12), 2679(EM6), 2680(ST12), 2681(SM6), 2682(IR4), 2683(SM6), 2684(SM6), 2685(IR4), 2686(EM6), 2687(EM6), 2688(EM6), 2689(EM6), 2690(EM6), 2691(EM6)c, 2692 (ST12), 2693(ST12), 2694(HW4)c, 2695(IR4)c, 2696(SM6)c, 2697(ST12)c.

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JANUARY: 2698(PP1), 2699(PP1), 2700(HY1), 2701(SA1), 2702(SU1), 2703(ST1), 2704(ST1), 2705(SU1), 2706 (HY1), 2707(HY1), 2708(HY1), 2709(PO1), 2710(HY1), 2711(HY1), 2712(ST1), 2713(HY1), 2714(PO1), 2715 (ST1), 2716(HY1), 2717(SA1), 2718(SA1), 2719(SU1)c, 2720(SA1)c, 2721(ST1), 2722(PP1)c, 2733(PO1)c, 2724 (HY1)c, 2725(ST1)c.

FEBRUARY: 2726(WW1), 2727(EM1), 2728(EM1), 2729(WW1), 2730(WW1), 2731(EM1), 2732(SM1), 2733(WW1), 2734(SM1), 2735(EM1), 2736(EM1), 2737(PL1), 2738(PL1), 2739(PL1), 2740(PL1), 2741(EM1), 2742(ST2), 2743(EM1), 2744(WW1), 2745(WW1), 2746(SM1), 2747(WW1), 2748(EM1), 2749(WW1), 2750(WW1)c, 2751 (EM1)c, 2752(SM1)c, 2753(PL1)c, 2754(ST2)c, 2755(PL1).

MARCH: 2756(HY2), 2757(IR1), 2758(AT1), 2759(CO1), 2760(HY2), 2761(IR1), 2762(IR1), 2763(HY2), 2764 (ST3), 2765(HY2), 2766(HW1), 2767(SA2), 2768(CO1), 2769(IR1), 2770(HY2), 2771(SA2), 2772(HY2), 2773 (CO1), 2774(AT1), 2775(IR1), 2776(HY2), 2777(HY2), 2778(SA2), 2779(ST3), 2780(HY2), 2781(HY2)c, 2782 (HW1)c, 2783(SA2)c, 2784(CO1), 2785(CO1)c, 2786(IR1)c, 2787(ST3)c, 2788(AT1)c, 2789(HW1).

APRIL: 2790(EM2), 2791(SM2), 2792(SM2), 2793(SM2), 2794(SM2), 2795(SM2), 2796(SM2), 2797(SM2), 2798 (EM2), 2799(EM2), 2800(EM2), 2801(EM2), 2802(ST4), 2803(EM2)c, 2804(SM2)c, 2805(ST4)c.

MAY: 2806(SA3), 2807(WW2), 2808(HY3), 2809(WW2), 2810(HY3), 2811(WW2), 2812(HY3), 2813(WW2), 2814(HY3), 2815(WW2), 2816(HY3), 2817(HY3), 2818(SA3), 2819(WW2), 2820(SA3), 2821(WW2), 2822 (WW2)c, 2823(HY3), 2824(SA3), 2825(HY3), 2826(SA3)c, 2827(HY3)c.

JUNE: 2828(SM3), 2829(EM3), 2830(EM3), 2831(IR2), 2832(SM3), 2833(HW2), 2834(IR2), 2835(EM3), 2836 (IR2), 2837(IR2), 2838(SM3), 2839(SM3)c, 2840(IR2)c, 2841(HW2)c, 2842(EM3)c, 2843(ST5), 2844(ST5), 2845 (ST5), 2846(ST5)c.

JULY: 2847(PO2), 2848(SU2), 2849(HY4), 2850(PO2), 2851(HY4), 2852(PO2), 2853(SU2), 2854(HY4), 2855 (PO2), 2856(PO2), 2857(PO2), 2858(SA4), 2859(SU2), 2860(SA4), 2861(PO2), 2862(SA4), 2863(HY4), 2864 (HY4), 2865(HY4), 2866(HY4), 2867(HY4), 2868(PO2)c, 2869(SA4)c, 2870(SU2)c, 2871(HY4), 2872(HY4)c, 2873(SU2), 2874(SA4).

AUGUST: 2875(WW3), 2876(WW3), 2877(WW3), 2878(SM4), 2879(ST6), 2880(EM4), 2881(SM4), 2882(EM4), 2883(WW3), 2884(EM4), 2885(SM4), 2886(WW3), 2887(EM4), 2888(WW3), 2889(AT2), 2890(AT2), 2891 (AT2), 2892(AT2), 2893(AT2), 2894(AT2), 2895(AT2), 2896(AT2), 2897(AT2), 2898(AT2), 2899(AT2), 2900 (AT2), 2901(AT2), 2902(SM4), 2903(ST6), 2904(ST6), 2905(SM4), 2906(ST6), 2907(EM4), 2908(ST6), 2909 (EM4), 2910(ST6), 2911(EM4), 2912(SM4), 2913(ST6), 2914(WW3)c, 2915(ST6)c, 2916(EM4)c, 2917(SM4)c.

c. Discussion of several papers, grouped by divisions.